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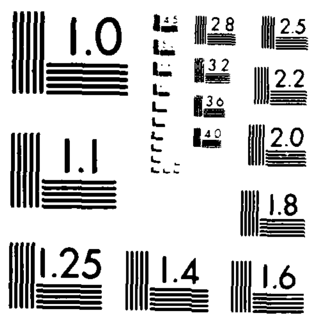

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WOODS HOLE OCEANOGRAPHIC INSTITUTION/ MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JOINT
PROGRAM
IN
OCEANOGRAPHY
AND
OCEAN ENGINEERING

DOCTORAL DISSERTATION

LATE PALEOGENE (EOCENE TO OLIGOCENE)
PALEOCEANOGRAPHY OF THE NORTHERN NORTH ATLANTIC

BY

KENNETH GEORGE MILLER

NOVEMBER 1982

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20.

Seismic stratigraphic evidence indicates that a major change in abyssal circulation occurred in the latest Eocene-earliest Oligocene of the North Atlantic. Reflector R4 reflects a change from weakly (Eocene) to vigorously circulating bottom water (early Oligocene). Sediment distribution studies indicate a northern source for this bottom water, probably from the Arctic via the Norwegian-Greenland Sea/Faeroe-Shetland Channel. Current-controlled sedimentation and erosion continued through the Oligocene; however, above reflector R3 (upper Oligocene), the general intensity of abyssal currents decreased. Above reflector R2 (lower Miocene) a further reduction in abyssal currents resulted in more coherent current-controlled sedimentation and a major phase of sediment drift development. Paleontological and stable isotopic data support these interpretations. In the Bay of Biscay, a major $\delta^{18}O$ increase began in the late Eocene, culminated in a rapid increase just above the Eocene/Oligocene boundary. Major deep-sea benthic foraminiferal changes occurred between the middle Eocene and earliest Oligocene: an agglutinated assemblage was replaced by a calcareous assemblage (abyssal Labrador Sea), and an indigenous Eocene calcareous fauna became extinct (abyssal Bay of Biscay). In shallower Atlantic sites (< 3km paleodepth), a Nuttallides truempyi assemblage was replaced by an assemblage of long- and wide-ranging taxa in the early late Eocene. These faunal and isotopic changes represent the transition from warm, old, corrosive Eocene bottom waters to colder, younger (lower CO_2, higher pH, hence less corrosive) early Oligocene bottom waters.

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LATE PALEOGENE (EOCENE TO OLIGOCENE) PALEOCEANOGRAPHY OF THE NORTHERN NORTH ATLANTIC

by

Kenneth George Miller

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

November 1982

DOCTORAL DISSERTATION

Prepared for the Office of Naval Research under Contract N00014-79-C-0071 and partially funded by a Phillips Petroleum Fellowship.

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LATE PALEOGENE (EOCENE TO OLIGOCENE) PALEOCEANOGRAPHY OF THE NORTHERN NORTH ATLANTIC

by

KENNETH GEORGE MILLER

A.B., Rutgers College, New Brunswick, NJ
(1978)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

at the

WOODS HOLE OCEANOGRAPHIC INSTITUTION
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

October, 1982

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Accepted by: Hans Schouten
Chairman, Joint Committee in Marine Geology and Geophysics

LATE PALEOGENE (EOCENE TO OLIGOCENE) PALEOCEANOGRAPHY OF THE NORTHERN NORTH ATLANTIC

by
KENNETH GEORGE MILLER

Submitted to the Woods Hole Oceanographic Institution/Massachusetts Institute of Technology Joint Program in Oceanography on 13 September 1982 in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

Seismic stratigraphic evidence from the western and northern North Atlantic indicates that a major change in abyssal circulation occurred in the latest Eocene to earliest Oligocene. In the northern North Atlantic, the widely-distributed reflector R4 correlates with an unconformity that can be traced to its correlative conformity near the top of the Eocene. This horizon reflects a change from weakly circulating (Eocene) to vigorously circulating bottom water (early Oligocene). Sediment distribution patterns provide evidence for strong contour-following bottom water flow beginning at reflector R4 time; this suggests a northern source for this bottom water, probably from the Arctic via the Norwegian-Greenland Sea and Faeroe-Shetland Channel. Erosion and current-controlled sedimentation continued through the Oligocene; however, above reflector R3 (middle to upper Oligocene), the intensity of abyssal currents decreased. Above reflector R2 (upper lower Miocene) current-controlled sedimentation became more coherent and a major phase of sedimentary drift development began. This resulted from further reduction in speeds and stabilization of abyssal currents.

Paleontological and stable isotopic data support these interpretations. In the Bay of Biscay/Goban Spur regions, a major $\delta^{18}O$ increase began at ~ 38 Ma (late Eocene), culminating in a rapid (< 0.5 my) increase in $\delta^{18}O$ just above the Eocene/Oligocene boundary (~ 36.5 Ma). A rapid $\delta^{13}C$ increase also occurs at ~ 36.5 Ma in these sites. Major changes in benthic foraminiferal assemblages also occurred between the middle Eocene and the earliest Oligocene: 1) In the Labrador Sea, a predominantly agglutinated assemblage was replaced by a calcareous assemblage between the middle Eocene and early Oligocene; 2) In the abyssal (> 3km) Bay of Biscay, an indigenous Eocene calcareous fauna including *Nuttallides truempyi*, *Clinapertina* spp., *Abyssammina* spp., *Aragonia* spp., and *Alabamina dissonata* became extinct between the middle Eocene and earliest Oligocene; 3) In shallower sites (< 3km paleodepth) throughout the Atlantic, a *Nuttallides truempyi*-dominated assemblage was replaced by a *Globocassidulina subglobosa-Gyroidinoides-Cibicidoides ungerianus-Oridorsalis* assemblage in the early late Eocene (~ 40-38.5 Ma). These faunal and isotopic changes represent the transition from warm, old, corrosive Eocene bottom waters to colder, younger (lower CO_2 and higher pH, hence less corrosive) early Oligocene bottom waters.

Thesis Co-supervisor: William A. Berggren Title: Senior Scientist
Thesis Co-supervisor: Brian E. Tucholke Title: Associate Scientist

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Micropaleontology Press and Nature Magazine are acknowledged for permission to reproduce Appendix 1 and 2, respectively.

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Finally, I thank my wife Karen for her support. This thesis is dedicated to her.

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CURRICULUM VITAE

KENNETH GEORGE MILLER
Stratigrapher/Micropaleontologist

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Family Status: Married to Karen Clark Miller.

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1982 Ph.D., WHOI/MIT Joint Program in Oceanography. Thesis title: "Late Paleogene (Eocene to Oligocene) paleoceanography of the northern North Atlantic."

Professional Experience:

1976-1978 Research Assistant to R. K. Olsson, Rutgers University, Department of Geological Sciences.
1977 Princeton-Yellowstone Bighorn Research Association Field program.
1978-1982 Graduate Research Assistant, Woods Hole Oceanographic Institution.
1980 Knorr 80 Cruise (Multichannel Seismic Cruise).
1980 Instructor, Sea Education Association.
1979-present Presented 12 papers at 1 regional, 3 international, and 5 national meetings.

Professional Societies:

American Association of Petroleum Geologists.
American Geophysical Union.
North American Micropaleontological Section of SEPM.
Sigma Xi.
Cushman Foundation for Foraminiferal Research.

Academic Awards and Grants:

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Phillips Petroleum Graduate Fellowship.

I have accepted a post-doctoral fellowship at Lamont-Doherty Geological Observatory of Columbia University following my tenure at WHOI.

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PREFACE

"To many geologists...[the description and correlations of local sections] make up the whole of stratigraphy, which is considered profoundly boring by all but those immediately concerned with the specific descriptions and correlations. But we believe that these, important and indispensible as they are, are but the means to a further end that constitutes the real core and interest of stratigraphy--namely, the interpretation of the stratigraphic record, both the rocks and their contained fossils, in terms of the past history of the earth."

Dunbar and Rodgers,
Principles of Stratigraphy
1957
(emphasis mine)

CHAPTER 1: INTRODUCTION

"Below a depth of 600 feet the ocean floor is...touched by currents so gentle as to have little effect on the bottom sediment...a continuous record of all geologic time may be present in parts of the ocean floor."

Dunbar and Rodgers (1957)

The Deep Sea Drilling Project has demonstrated that the deep-sea stratigraphic record is punctuated by numerous hiatuses, many of which resulted from erosion by vigorously circulating bottom waters. One of the most dramatic hiatuses attributed to such erosion occurred in the Late Paleogene of the Atlantic, Southern, and Pacific Oceans. This thesis investigates the age and cause of this event in the North Atlantic and evaluates its effect on the paleoenvironment of the deep sea.

Deep and bottom waters formed in the Norwegian-Greenland Sea today overflow the aseismic ridge between Greenland and Scotland, forming a major constituent of modern North Atlantic Deep Water (NADW). This overflow influences hydrographic properties as far away as the North Pacific Ocean (e.g. Reid and Lynn, 1971). It also profoundly effects sediment distribution, not only through erosional/depositional effects (e.g. Heezen et al., 1966) but also through its importance in fractionation of calcium carbonate and silica between basins (e.g. Berger, 1970). For over a decade, it has been known that overflow of the Greenland-Scotland Ridge had geologically significant effects well back into the Tertiary (Jones et al., 1970). The initial entry of such northern bottom waters into the North Atlantic represents a critical threshold in the development of global bottom-water circulation.

Considerable debate, based upon differing lines of evidence, exists as to the timing of initial vigorous deep circulation in the North Atlantic resulting from bottom water formation in high northern latitudes. Three distinct events in the benthic faunal, isotopic, and lithostratigraphic records have been proposed as representing the initial formation. 1) Based upon increased deposition of biosiliceous sediments in the North Atlantic, Berggren and Hollister (1974; 1977) suggested that the first influx and upwelling of bottom water from the Norwegian-Greenland Sea/Arctic Ocean occurred in the early Eocene. 2) Based upon

changes in benthic foraminiferal assemblages and isotopic composition, Schnitker (1979) and Blanc et al. (1980) suggested that the first entry of northern bottom waters into the North Atlantic began in the middle Miocene. 3) Based upon a change from agglutinated to calcareous benthic foraminiferal assemblages in the Labrador Sea near the end of the Eocene, Miller et al. (1982; Appendix 1), suggested that significant influx of northern bottom waters began in the late Eocene to early Oligocene. Sucn ambiguity results from the nature of the evidence interpreted, for faunal, lithologic, and isotopic evidence are rarely by themselves diagnostic of the nature of abyssal circulation changes (Johnson, 1982; Miller and Tucholke, in press; Appendix 3; Miller, in press a).

The seismic stratigraphic record (and to some extent the rock stratigraphic record) provides less ambiguous evidence for changes in the intensity of bottom water circulation than do faunal or isotopic changes alone, although seismic and rock stratigraphic studies rely upon biostratigraphy to identify the age of events. The development of many regional deep-sea unconformities, especially those that show significant truncation and erosion of lower horizons, are evidence of strong bottom-water flow. Such unconfomities are most clearly manifested in the seismic stratigraphic record (Vail et al., 1977; Tucholke and Mountain, 1979; Miller and Tucholke, in press; Appendix 3). In addition, stratal patterns within seismic sequences such as the development of drift deposits, moats, and sediment waves document the influence of strong currents on deep-sea sedimentation. Regional seismic stratigraphic studies, therefore, are perhaps the most useful tool for delineating the relative timing and importance of current changes.

This thesis addresses the problem of the timing, effects, and causes of the first geologically significant influx of bottom water from northern sources into the North Atlantic. The problem is addressed in three ways. 1) The seismic stratigraphic and lithostratigraphic records of the northern North Atlantic (i.e. the region north of ~ 45^{o}N latitude and south of the Greenland-Scotland Ridge)(Fig. 1) are examined and biostratigraphically dated in order to formulate a testable model for the development of Cenozoic abyssal circulation in the North Atlantic. 2) Eocene to Oligocene deep-sea benthic foraminiferal assemblage and

isotopic changes in the northern North Atlantic are examined. This documents the relationship among faunal, isotopic, and abyssal circulation changes in the Late Paleogene. 3) Possible controls (e.g. climatic and tectonic changes) on the development of Cenozoic abyssal circulation in this region are evaluated. This study differs from most earlier studies, in that it does not depend soley upon faunal and isotopic data to interpret the nature of the major abyssal circulation changes. Rather, it uses these data in a supportive role, thus reducing some of the ambiguities that occur in paleoceanographic interpretations based on such records alone.

Most of the detailed data brought to bear on this issue have been published (or are pending publication) elsewhere and are appended here. Appendix 1 proposes that middle Eocene to early Oligocene benthic faunal changes in the North Atlantic were related to the first significant formation of bottom water of northern origin. The circulation model is developed in Appendix 3, while Appendixes 2, 4, and 5 establish the relationship of faunal and isotopic changes with respect to the circulation model.

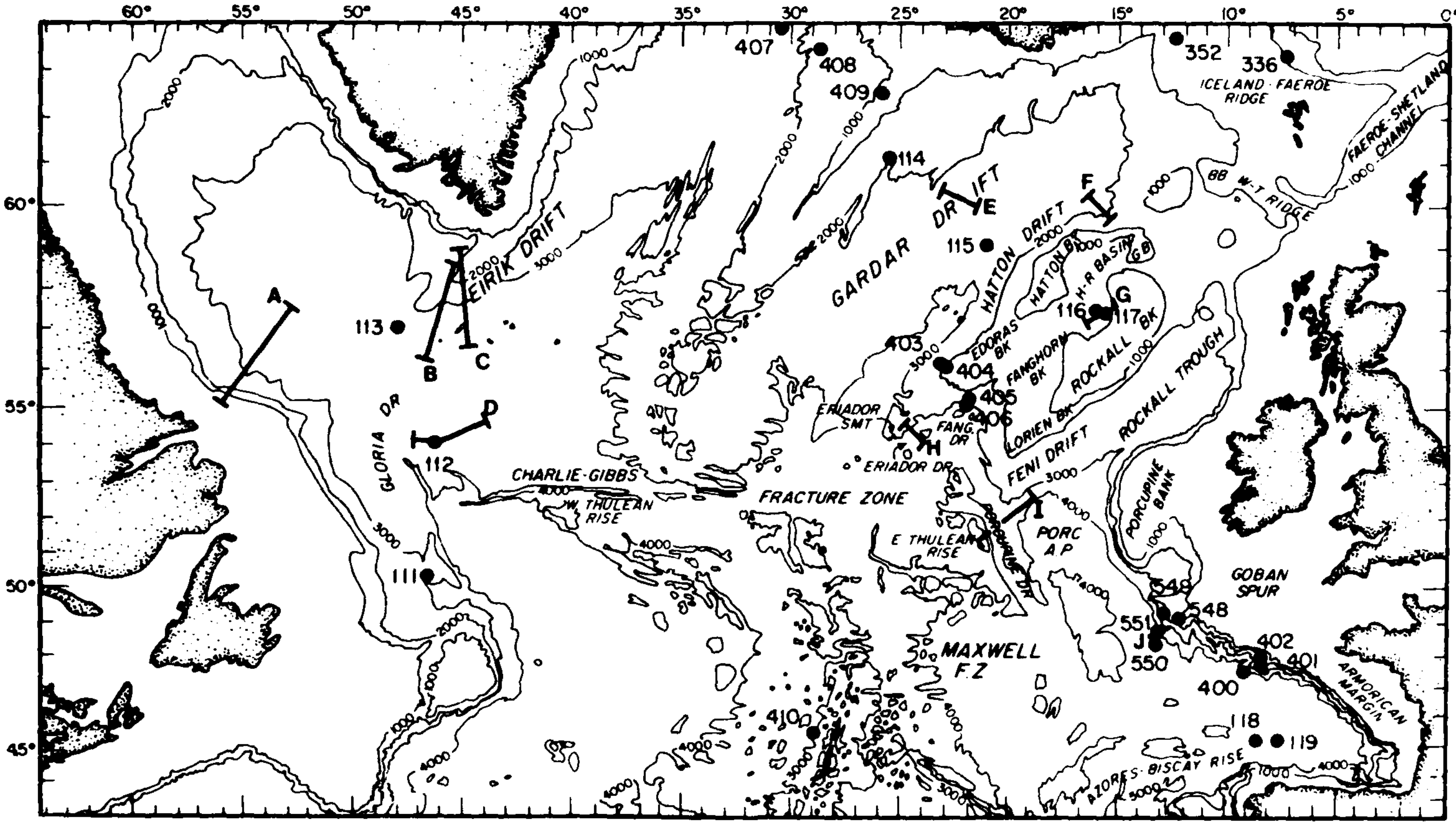

Figure 1. Bathymetric location map of the northern Atlantic with locations of DSDP sites and major sediment drifts. Contour interval 1000m. Sections labeled A through J are illustrated in Figures 4-13 and 15. H-R = Hatton-Rockall Basin; GB = George Bligh Bank; BB = Bill Bailey Bank

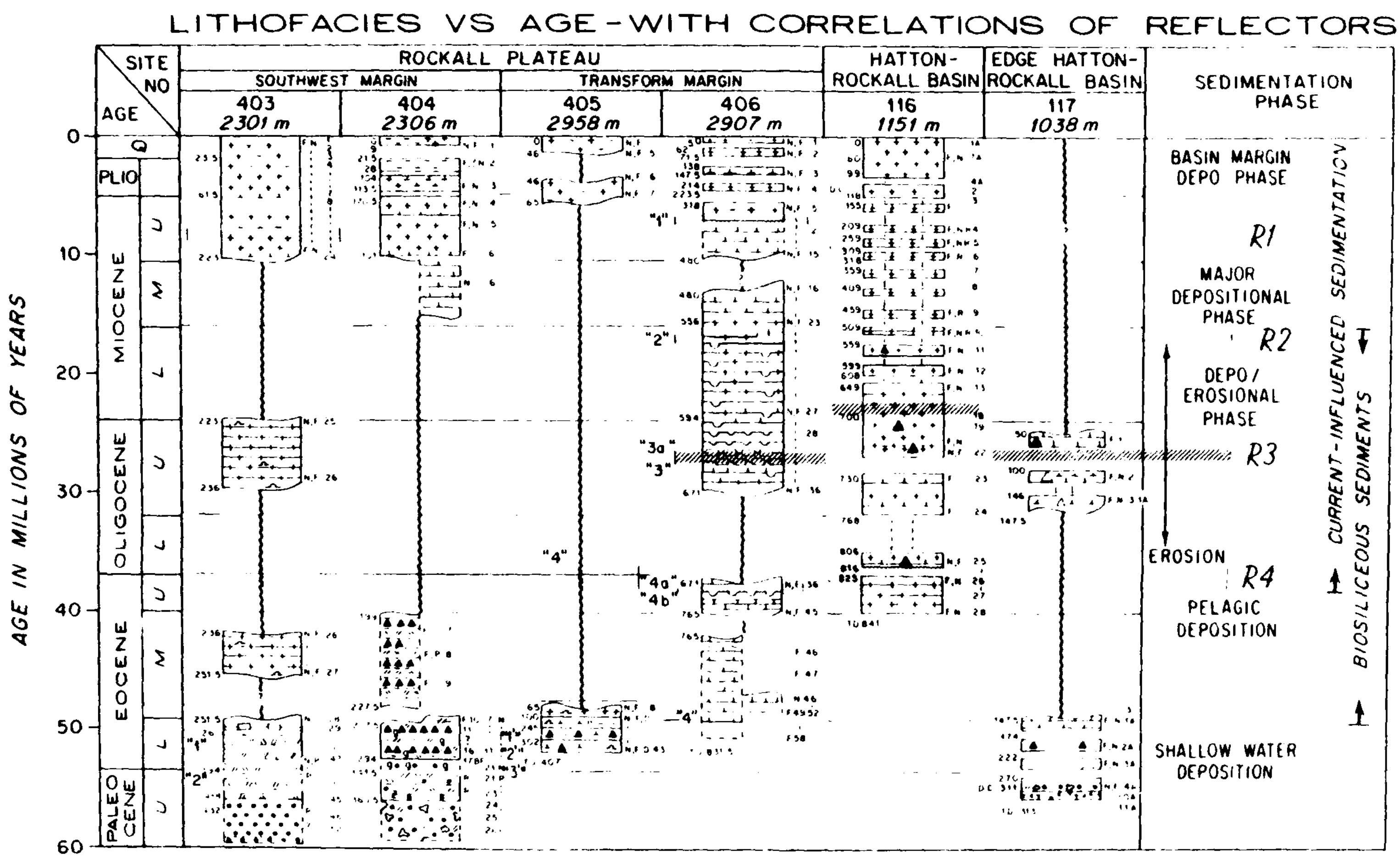

Figure 2. Age versus lithofacies for DSDP sites in Rockall region with correlation of major reflectors. Site locations in Figure 1. Lithologic symbols follow standard "Initial Reports" format. To left of columns are subbottom depths in meters (T.D. = total depth); to right are indicated core number and fossil group on which age is based (N = nannoplankton; F = foraminifers, R = radiolaria, P = palynomorphs, BF = benthic foraminifera, D = diatoms, X/S = extrapolated by sedimentation rate). Heavy wavy lines show hiatuses; dashed lines show inferred continuous sedimentation. Numbers in quotes at left of columns are reflector numbers used in individual site reports by Montadert, Roberts et al. (1979). After Miller and Tucholke (in press; Appendix 3).

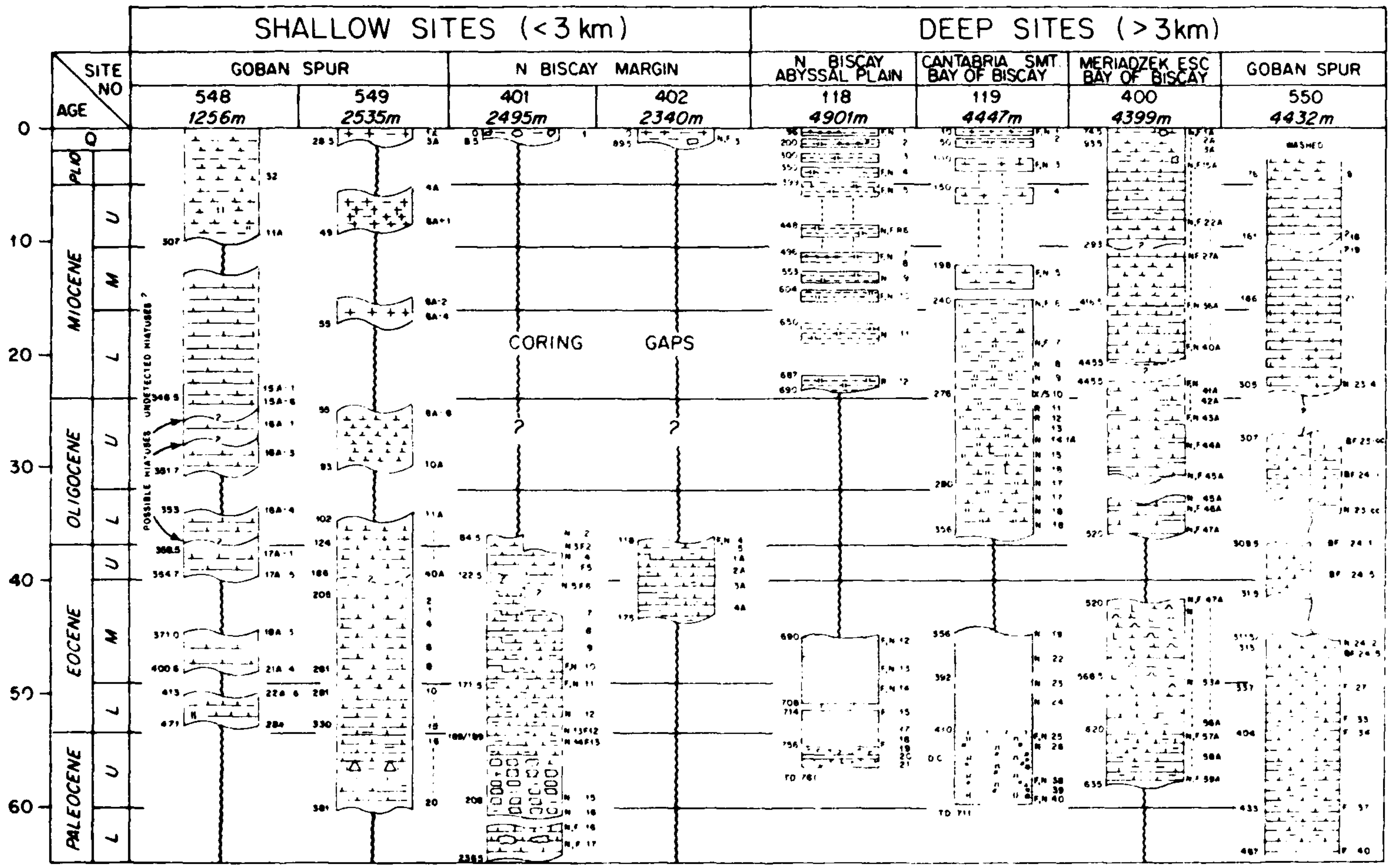

Figure 3. Age versus lithofacies for Tertiary sediments recovered at DSDP sites in the Bay of Biscay. Explanation in Figure 2. After Miller et al. (in press; Appendix 5).

CHAPTER 2: DEVELOPMENT OF ABYSSAL CIRCULATION IN THE NORTHERN NORTH ATLANTIC: SEISMIC AND LITHOSTRATIGRAPHIC EVIDENCE

Introduction

The presence of strong abyssal currents is best documented by the development of regional deep-sea unconformities that are observed as seismic discontinuities. The first unambiguous evidence of strong bottom-current activity reported in the North Atlantic is the prominent erosional unconformity (Horizon A^u) that occcurs beneath the continental rise of eastern North America. Tucholke (1979) and Tucholke and Mountain (1979) demonstrated that this erosion occurred at some time between the late Eocene and earliest Miocene. They suggested that the unconformity was caused by a precursor to the modern southerly-flowing Western Boundary Undercurrent (Heezen et al., 1966) which contains a significant component of Greenland-Scotland Ridge overflow water. Unfortunately, where cored, the hiatus at Horizon A^u is too long to resolve firmly the timing of this abyssal circulation event.

The sedimentary record recovered in the northern North Atlantic (north of ~ 45^o N) (Fig. 1; Figs. 2,3) is more complete. A widespread seismic reflector occuring in this region variously termed "R" (Jones et al., 1970; Ruddiman, 1972), or "R4" (Roberts, 1975; Roberts et al., 1979; Miller and Tucholke, in press; Appendix 3), figures prominently in the interpretation of abyssal circulation history because it divides current-influenced sedimentation above from largely pelagic and downslope sedimentation below (Figs. 4-12). Reflector R4 correlates with a prominent unconformity found in boreholes drilled in the Rockall and Biscay regions (Figs. 2,3). In the Rockall Trough and Porcupine Abyssal Plain regions (Fig. 1), it truncates underlying strata (Figs. 5,6; figs. 29,30,32 in Roberts, 1975). Because of these relationships, and because it approximately correlates with Horizon A^u in time, reflector R4 seems to mark initial strong abyssal circulation in the North Atlantic.

I have traced reflector R4, overlying reflectors, and underlying reflectors throughout the northern North Atlantic and dated them at boreholes (Fig. 1) using single channel seismic reflection data of

Lamont-Doherty Geological Observatory (Figs. 4-9,11,12), Woods Hole Oceanographic Institution, U.S. Navy, and DSDP Legs 12 and 48. In addition, multichannel data from the Canadian Geological Survey/Federal Institute for Geosciences and Natural Resources (BGR)(Figs. 10,14), the British National Oil Company (BNOC)/Institute of Geological Sciences (IGS) Edinburgh (Fig. 24), DSDP Leg 48 (Montadert, Roberts et al., 1979), and Leg 80 (Fig. 13)(de Graciansky, Poag et al., in preparation) were examined. This chapter discusses the pre-R4 sequences in the northern North Atlantic, establishing that little evidence of abyssal currents is found prior to reflector R4 time. The age and significance of reflector R4 are then discussed, establishing that this horizon marks the most important change in sedimentary regime in the northern North Atlantic. The post-R4 sequences are then examined and dated, and post-R4 evidence of abyssal circulation changes is investigated. Finally, a model for the development of abyssal circulation in the northern North Atlantic is presented.

Pre-R4 Sequences

The pre-R4 sequences are generally poorly resolved in the single channel and multichannel data examined (Figs. 4-12). In the Labrador Sea, most prominent are strong seismic reflectors thought to be Lower Tertiary basaltic rocks (Figs. 10-12). These basalts are probable age equivalents of some of the extrusives in East Greenland, northern Britain, Davis Straits, and Voring Plateau (Fitch et al., 1974). This "Thulean" volcanic event probably coincided with the initiation of sea-floor spreading in the Norwegian-Greenland Sea about Anomaly 24 time (latest Paleocene to earliest Eocene)(Berggren and Schnitker, in press).

Several strong intra-sedimentary seismic reflectors underlie reflector R4 in the Rockall Trough and Porcupine Abyssal Plain; in general, these pre-R4 reflectors result from pelagic basin fill (Figs. 4,5) or downslope sedimentation. In the southern Rockall Trough and eastern Porcupine Abyssal Plain, Dingle et al. (1982) observed two such reflectors, the deeper termed "Shackleton" and the shallower termed "Charcot." In the Rockall Trough, Roberts (1975) observed three pre-R4

reflectors; he called these Z, X, and Y in ascending stratigraphic order. The relationships between the horizons noted by Roberts (1975) and those of Dingle et al. (1982) are not clear; comparison of their published profiles with profiles herein (V29-09; V23-05) suggests that reflector Y probably corresponds to "Shackleton" and that reflector X probably corresponds to "Charcot."

Reflector Z can be constrained only to the Upper Cretaceous (Roberts et al., 1981); Roberts (1975) noted that sediments below reflector Z consist of pelagic drapes. An exception to this may occur along the margin of the Rockall Trough near Lorien Bank (Fig. 1) where reflector Z is flat lying; Roberts (1975) suggested that this may represent gravity fill. Reflector Y is of late Paleocene age (Roberts et al., 1981); in general, the Z-Y sequence also consists primarily of drapes conformable with basement (Roberts, 1975), although fan deposition may occur in the Z-Y interval (fig. 32 in Roberts, 1975). Reflector X is a post-Paleocene reflector that merges with reflector R4 in the Biscay region (Roberts et al., 1981) and is probably of early or middle Eocene age; it apparently also occurs on the southwest margin of Rockall Plateau, where it drapes over the faulted acoustic basement (fig. 26 in Roberts, 1975).

Evidence of current influences in the R4-X interval are debatable. Dingle et al. (1982) noted apparent lensing between reflector Charcot (= X) and reflector R4 (= their reflector Challenger) in the southern Rockall Trough; they suggested that this indicated current influences on sedimentation in the pre-R4 interval. However, examination of their published data suggests that they traced the top of a high amplitude unit as reflector R4; an overlying reflector (reflector R3, see below) onlaps reflector R4, and generally represents the top of the high amplitude unit. Thus, some of the differential thickening that they noted probably occurs not in the pre-R4 interval, but in the post-R4 interval (between reflector R4 and reflector R3; their figure 4). In addition, reflector X is truncated by reflector R4 (fig. 29 in Roberts, 1975); therefore, apparent lensing in the R4 to X (= Charcot) interval may be due to erosional truncation at the level of reflector R4. This is illustrated by the erosion and truncation of horizons by reflector R4 shown in figure 5; the thickness variations (e.g. Fig. 5) apparent in the pre-R4 interval

are not depositional phenomena but are lenslike remnants formed by erosion at the level of reflector R4.

In the Rockall Plateau area, the pre-R4 sequences are poorly-defined (Figs. 4,8,9). Along margins of the Hatton-Rockall basin (Figs. 1,4), Roberts (1975) noted that variations in thickness of the pre-R4 series are attributable to syndepositional faulting. In general, the pre-R4 series on Rockall Plateau is characterized by extremely high sedimentation rates (> 70 m/m.y.; Roberts et al., 1979) associated with the rapid subsidence of Rockall Plateau during the late Paleocene to early Eocene (Laughton, Berggren et al., 1972; Berggren, 1974; Roberts et al., 1979).

West of Rockall Plateau in the Iceland Basin, the pre-R4 interval thickens westward toward the flanks of the Reykjanes Ridge (profile V27-06; profile Kane 70C, fig. 14 in Ruddiman, 1972). The cause of this thickening is not known. Roberts (1975) suggested that it resulted from a westward increase in sedmentation rate in the pre-R4 interval. Still, it is not clear why such a radical east to west change in sedimentation rate occurred over a distance of less than 150km. Erosion of the pre-R4 sequence along the western margin of Rockall Plateau at the level of reflector R4 would seem a more likely explanation for this thickness variation; however, poor resolution of pre-R4 reflector in the Iceland Basin preclude proving this.

In the southern Labrador Sea, several prominent seismic reflectors occur above the presumed upper Paleocene basalts and below reflector R4 in multichannel profiles (Line BGR 1; Fig. 10). Two sedimentary seismic reflectors, designated here P1 and P2, bracket a series of horizons that strongly onlap reflector P2 (Fig. 10). Because of the proximity of the NNW end of BGR 1 to the Greenland Margin (Fig. 1), the progressive onlap of reflector P1 may represent a lowstand deposit (sensu Vail et al., 1977) resulting from progressive outbuilding during a eustatic lowering of sea level. Crustal age underlying reflectors P1 and P2 on BGR line 1 (~ shotpoint 4400; Fig. 10) is Late Cretaceous (pre-Anomaly 31; Srivastava, 1978) and the supposed lowstand fan could be the result of any one of a series of Late Cretaceous to Eocene eustatic lowerings of sea level (Vail et al., 1977). However, if the strong reflectors are

assumed to be extrusive (upper Paleocene) basalts, then the lowstand may correspond to an early Eocene major sea-level lowstand (Vail et al., 1977). In any case, the flat-lying reflectors of the pre-R4 interval on BGR 1 (Fig. 7) show no evidence of differential deposition or development of sediment waves; current effects appear to be limited to the post-R4 section.

The best evidence for pre-late Eocene current effects comes from the western basin (North American) of the North Atlantic. On the western Bermuda Rise, Mountain (1981) found unusual wave-like variations in thickness between horizons A^c (lower to middle Eocene) and A^* (upper Maestrichtian). He attributed these to possible Paleocene to early Eocene syndepositional control by bottom currents or to erosion at the level of Horizon A^c. Unfortunately, the upper horizon has not been firmly established as Horizon A^c; it is possible that it is equivalent to Horizon A^u and therefore represents a later erosional event. However, if the "waves" are attributed to early Eocene erosion at the level of Horizon A^c, a major erosional event must have occurred in the early Eocene.

The possibility that such a circulation event occurred in the early Eocene North Atlantic would support Berggren and Hollister's (1974) contention that increased early to middle Eocene deposition of biosiliceous sediments in the North Atlantic resulted from the first formation, sinking, and upwelling of cold, Arctic waters in the northern North Atlantic. This correlation is reasonable, but it is possible that the biosiliceous sedimentation was stimulated by other mechanisms (see Chapter 4). The apparent lack of similar wave-like features like those noted by Mountain (1981) elsewhere in the North Atlantic suggests that the event was not due to the early Eocene entry of bottom waters from the north. Still, pre-R4 data in the northern North Atlantic are generally poorly resolved, and the possiblity exists that some pre-R4 current-influenced deposits remain undetected.

Reflector R4 and Horizon A^u denote the most dramatic change in sedimentary regime in the Cenozoic stratigraphic record of the North Atlantic. Pre-R4 (and similarly, pre-A^u) evidence for any significant abyssal circulation is debatable, but current influences in the post-R4 interval are well developed, as discussed below.

Reflectors R4 and R3

Distribution

Reflector R4 shows the earliest unambiguous and regionally important evidence for strong abyssal circulation in the northern North Atlantic. Differential thickening of sedimentary sequences that is typical of current-controlled deposition occurs above this horizon (Figs. 4-13). In most of the pre-R4 section strata are either largely conformable with basement (typical of pelagic accumulation), attributable to fan development, or attributable to syndepositional faulting. Reflector R4 is an interbasinal reflector which has been reported throughout the Rockall region (Roberts, 1975; Jones et al., 1970), the Iceland Basin (Ruddiman, 1972), the Porcupine Abyssal Plain (Dingle et al., 1982), the Bay of Biscay (Roberts et al., 1979), and the southern Labrador Sea (Egloff and Johnson, 1975). Reflector R4 originally was first defined in the Rockall Plateau region (Jones et al., 1970; Roberts, 1975); it has been identified in boreholes drilled there as a synchronous late Eocene to earliest Oligocene seismic reflector (within uncertainties of correlation into the boreholes and of biostratigraphic age assignments; see below)(Miller and Tucholke, in press; Appendix 3). However, a continuous and unequivocal tracing of reflector R4 from the Rockall Plateau boreholes into these other regions studied is not possible. This situation led Dingle et al. (1982) to use the term "Challenger horizon" for a reflector that they thought was equivalent to reflector R4. However, similar seismic character (amplitude, stratigraphic relations of major reflectors) and stratigraphic position of a major reflector observed throughout the northern North Atlantic suggest that reflector R4 occurs in all these regions. Borehole correlations in the Labrador Sea, Bay of Biscay, and Goban Spur region (Fig. 1) support this contention.

Reflector R4 is overlain by reflector R3 in the Rockall region, Porcupine Abyssal Plain, and Labrador Sea (Figs. 4-13). As with reflector R4, identification of reflector R3 outside of the Rockall region (Fig. 4) is tentative, because a continuous and unequivocal tracing of reflector R3 into other regions is not possible. Reflector R3 is of middle to late Oligocene age (Miller and Tucholke, in press;

Appendix 3). The R3-R4 seismic interval commonly has high amplitude, discontinuous reflectors that tend to obscure the underlying reflector R4 (Fig. 4)(Roberts, 1975). Reflector R3 has no consistent age or lithologic correlation (i.e. it correlates with the middle Oligocene at Sites 406 and 117 and the uppermost Oligocene at Site 116; Fig. 2). In fact, the high amplitude, discontinuous nature of reflector R3 suggests that it may cap a sequence of cherty chalks (Roberts, 1975); the diachronous age correlations of reflector R3 may be explained if it is equivalent to such a diagenetic boundary.

Rockall region

Seismic stratigraphic relationships show that reflector R4 represents the most important erosional event in the Rockall region (i.e. between the Mid-Atlantic Ridge and the Irish Continental Margin; north of the Charlie-Gibbs Fracture Zone and south of the Greenland-Scotland Ridge; Fig. 1). Although reflector R4 generally has not been re-excavated by younger erosional events (with the possible exception of channels such as that noted at the foot of George Bligh Bank; fig. 35 in Roberts, 1975), erosion associated with reflector R4 consistently excavated and truncated older strata (Figs. 5,6; figs. 29,30,32,33 in Roberts, 1975; fig. 4 in Dingle et al., 1982). Reflector R4 in the Rockall area shows a strong correlation to the regionally important hiatus that straddles the Eocene/Oligocene boundary (Fig. 2), except possibly at Site 406 where borehole correlations (Miller and Tucholke, in press; Appendix 3) suggest that it may underlie the unconformity by as much as 45m.

The unconformity generally associated with reflector R4 is best developed along the margins of the basins (e.g. Sites 117, 403, 404, 405; Figs. 2), probably due to local intensification of abyssal currents by topographic boundaries. Away from basin margins the unconformity may not be present, for reflector R4 correlates with the uppermost Eocene to lower Oligocene section that appear to be continous within the resolution of biostratigraphy (e.g. Site 116; Fig. 2). Thus, the unconformity usually equivalent to reflector R4 can be traced to its correlative conformity (= seismic sequence boundary of Vail et al., 1977) near the top of the Eocene. The cause of reflector R4 where the section is

apparently conformable is not clear; it may result from an impedance contrast caused by a lithologic change associated with the changing hydrographic regime. It is also possible that the impedance contrast occurs across an as yet unresolved unconformity or diastem.

Reflector R3 onlaps reflector R4 near the margin of Rockall Plateau (Figs. 4,8,9; figs. 19,20,29,30,32,35 in Roberts, 1975); reflector R3, in turn, is often onlapped by overlying horizons (Figs. 4,6,9). The onlap of reflector R4 by reflectors biostratigraphically dated as Oligocene through late Miocene (Miller and Tucholke, in press; Appendix 3; see below) demonstrates that patterns of non-deposition and erosion resulting from vigorous bottom circulation have dominated the margin of Rockall Plateau since R4 time.

Differential thickening of strata between reflectors R3 and R4 indicates that initial development of sediment drifts began in the R3-R4 interval (Figs. 6-9). The development of such current-controlled depositional features is indicated by contorted internal reflectors and possible local development of sediment waves in the R3-R4 interval (Fig. 8). Still, the erosion that created reflector R4 resulted in a hiatus that often encompasses the R3-R4 interval (Figs. 2,3), demonstrating that the R3-R4 interval is primarily erosional, especially along the margin of Rockall Plateau.

In the Rockall region, several sedimentary ridges, both large and small, are built upon reflector R4, including a drift in the Hatton-Rockall Basin (Figs. 4;14), the Feni Drift (Figs. 5,6), Gardar Drift (Fig. 7), Hatton Drift (Fig. 8), and several unnamed drifts east of Eriador Seamount (named Eriador Drift herein; Fig. 9), south of Fanghorn Bank (named Fanghorn Drift herein; Fig. 14), and NW of the "elbow" formed between Bill Bailey and Faeroe Banks (Fig. 1). Accumulation rates increased (Table 1) in the Miocene both on these drifts and on drifts in the western North Atlantic (Blake, Greater Antilles, Bahama, and Hatteras Ridges; Ewing and Hollister, 1972; Tucholke and Mountain, 1979). Therefore, the drifts illustrated here, although present since the Oligocene, are composed primarily of Miocene and younger sediments (i.e. post-R2 sediments on Figs. 4-12). This is especially true along the shallower margins of the drifts, where currents are topographically

TABLE 1

ESTIMATES OF SEDIMENTATION RATES IN BASINS
IN THE NORTHERN NORTH ATLANTIC
(given in meters/million years)

BASIN	INTERVAL				
	post-R1 0-8 Ma	R1-R2 8-17 Ma	post-R2[1] 0-27 Ma	R2-R3 17-27 Ma	R3-R4 23-37 Ma
Hatton-Rockall Basin (Site 116; Figs. 2,4)					
estimated[2]	36	33	34	11	12
actual[3]	~ 45	~ 25	--	11	10
Fanghorn Drift (Site 406)					
estimated[2]	44	24	34	~ 7	~ 6
actual[3]	45	34	--	late Oligocene: 22 early Oligocene: 0	
Iceland Basin (Fig. 7)	--	--	36	26	18
Gardar Drift	--	--	46	30	--
Hatton Drift (Fig. 8)	--	--	21-23	12	18
Eriador Drift (Fig. 9)	--	--	31	22-35	~ 13
Feni Drift (Fig. 5)	--	--	--	post R3: 20	31
Porcupine Drift (Fig. 6)	--	--	31	26	18
Eirik Drift[4]	--	--	51	26	13

Table compiled by measuring intervals at depocenters of the sediment drifts for each interval on seismic profiles illustrated in Figures 4-9, assuming average interval velocity of 1750 m/sec. Not corrected for compaction. R3-R4 estimates are minima since no hiatuses are assumed to be present.

1 Reflector R1 not recognized.
2 Estimated from seismic stratigraphy.
3 Actual sedimentation rate computed accounting for hiatuses. (After Laughton, Berggren et al., 1972 and Montadert, Roberts et al., 1979; Site 116 Oligocene rates after Miller and Tucholke, in press; Appendix 3).
4 Reflector R2 identification speculative on Eirik Drift.

intensified and much of the section has been removed (or was never deposited). Since most DSDP sites have been located on the margins of the drifts (e.g. Sites 117, 403, 404, 405), it is easy to draw the erroneous conclusion that drift deposition began in the Miocene (e.g. Schnitker, 1980a). This is not the case, for drift development can be seen clearly in the Oligocene section between reflectors R3 and R4 and in the Oligocene to lower Miocene between reflectors R2 and R3 (Figs. 4-12).

Bay of Biscay/Porcupine Abyssal Plain/Goban Spur regions

In the Bay of Biscay/Goban Spur region, reflector R4 probably correlates with an unconformity straddling the Eocene/Oligocene boundary at Sites 548, 401, 402, 118, 119, 400A, and 550 (Fig. 3). However, this is not certain due to difficulties in tracing the horizon into these boreholes, incomplete coring, and poor placement of these boreholes for stratigraphic correlations of the Tertiary section. Throughout the abyssal portion of the Bay of Biscay, turbidite deposition dominates the sedimentary record; here, reflector R4 is often not well defined seismically, although it is present (e.g. Site 118; Laughton, Berggren et al., 1972). In areas shielded from turbidite deposition, such as Cantabria Seamount (Site 119; figs. 3,6 in Chapter 10 in Laughton, Berggren et al., 1972), a prominent horizon that correlates in time with reflector R4 is observed; on such topographic highs, the seismic character of reflector R4 is similar to that observed in the Rockall region.

Reflector R4 is well developed in the Porcupine Abyssal Plain region (Dingle et al., 1982; this study). In the western portion of this basin, a large (> 250km long) previously unnamed sediment drift is observed (Fig. 6). The Porcupine Drift (named herein) is a NW-SE trending sediment ridge developed against the eastern flank of the east Thulean Rise south of the Charlie-Gibbs Fracture Zone (Fig. 1). It may be considered a southern extension of the Feni Ridge (although the latter occurs in a different physiographic province, the Rockall Trough, and it has a different orientation, NNE-SSW). The post-R4 interval of the Porcupine Drift shows patterns of differential deposition and sedimentary waves (Fig. 6) that document the presence of strong abyssal circulation.

Labrador Sea

In the southern Labrador Sea, a prominent mid-sediment reflector was first noted by Jones et al. (1970) and Egloff and Johnson (1975), who suggested that it correlated with reflector R (= R4) in the Rockall region. Above this reflector, two large sediment drifts are developed: the Eirik Drift south of Greenland (Figs. 1,10,12) and the Gloria Drift (Figs. 1,11). Seismic comparison with the Rockall region and borehole correlations at Site 112 in the Gloria Drift (Fig. 1; fig. 5 in Appendix 1)(see below) suggest that the top of this mid-sediment reflector may be reflector R3, and that reflector R4 is seismically masked beneath this high-amplitude event over much of the southern Labrador Sea (Figs. 10-12). This conclusion needs to be tested by future drilling. The R3/R4 couplet has been traced from Site 112 throughout the Gloria Drift, but direct correlations into the Eirik Drift are blocked by basement interruptions at the extinct spreading axis. However, the similar seismic character of the R3/R4 couplet in the Gloria Drift and the Eirik Drift (cf. Figs. 11,12) suggests that reflector R4 occurs in the deep basin adjacent to the southern Greenland margin. A major seismic discontinuity thought to be equivalent to reflector R4 has also been noted in the deep basin adjacent to the eastern margin of Greenland by Featherstone et al. (1977).

It is not possible to trace the R3/R4 couplet from the southern Labrador Sea into the central and northern Labrador Sea in available single channel seismic data. North of the Gloria and Eirik Drifts, turbidite deposition dominates the sedimentary record in the upper 1km of section (see also Davies and Laughton, 1972). Unfortunately, seismic reflectors are generally not resolvable below about 1 sec (~ 1km) in the single channel seismic profiles examined; this prevents detecting reflectors R3/R4 which lie deeper than 1 sec. However, three distinct reflectors are observed in multichannel seismic data from the central and northern Labrador Sea (Lines BGR 17, 21, and 12; fig. 1 in Hinz et al., 1979): U, E/O, and E in descending stratigraphic order. It is suggested here that horizon E/O is equivalent in age to reflector R4, and that the event associated with reflector R4 affected the entire deep Labrador Sea including the lower continental rise of Labrador and Greenland.

Age of reflector R4

Jones et al. (1970) cored upper Oligocene sediments from immediately above reflector R4, establishing its age as pre-late Oligocene. Ruddiman (1972) suggested that reflector R4 was early Oligocene based upon its pinchout on crust older than Anomaly 13 (early Oligocene). Based upon corrlations to DSDP boreholes in the Rockall region, Roberts (1975) and Roberts et al. (1979) suggested that reflector R4 is late Eocene to early Oligocene. Miller and Tucholke (in press; Appendix 3) traced reflector R4 to DSDP boreholes throughout the northern North Atlantic; they used velocity-depth data obtained from sonobuoy measurements to determine subbottom depths, and then adjusted the placement of reflectors within geologically reasonable limits. The correlations obtained in this manner agree well with those obtained by Montadert, Roberts et al. (1979) and Roberts et al. (1979) who used synthetic seismograms computed from sonic logs to constrain the depth of reflectors drilled by Leg 48 in the Rockall region. Reflector R4 correlates with a major unconformity at Sites 403 and 404 that separates upper Miocene from Eocene strata, while at Sites 117 and 403 this reflector separates upper Oligocene from lower to middle Eocene strata (Fig. 2). The unconformity associated with reflector R4 can be traced to its apparent correlative conformity (= sequence boundary, sensu Vail et al., 1977) at three locations. 1) At Site 116 the horizon correlates with an apparently continuous section in an uncored interval separating upper Eocene from lower Oligocene strata (Fig. 2). 2) At Site 112 in the southern Labrador Sea, reflector R4 appears to lie at 0.41 sec and to correlate with the lower Oligocene section (Miller et al., 1982; Appendix 1). However, the reflector at 0.41 sec is the top of a high-amplitude unit that may obscure underlying horizons (Fig. 11). As suggested above, top of this high amplitude unit may be reflector R3, and reflector R4 may be masked; in fact, reflector R4 probably underlies the top of the high amplitude unit by 0.1 sec at Site 112 (profile V30-09, Fig. 11). Recomputing the depth of reflector R4 assuming that it lies at 0.51 sec suggests that it correlates with the uncored interval that straddles the Eocene/Oligocene boundary at Site 112 (fig. 5 in Appendix 1). 3) At Site 406 reflector R4 correlates with undifferentiated upper Eocene sediments underlying a major unconformity

separating upper Oligocene from upper Eocene strata (Fig. 2). Although the correlation into Site 406 is probably valid (see Appendix 3), correlation of reflector R4 with the lower Oligocene unconformity would still yield geologically a reasonable interval velocity (~ 1850 m/sec).

Given the record recovered, uncertainties in correlation into the boreholes, and biostratigraphic problems, the age of reflector R4 could range from ~ 40-35 Ma (time scale of Hardenbol and Berggren, 1978). However, based upon the correlation at Site 116 and the revised correlation at Site 112, Reflector R4 is probably latest Eocene to earliest Oligocene (~ 38-36 Ma).

Recent drilling in the Rockall region (Leg 81) and the Goban Spur (Leg 80) tends to support the age assignment of reflector R4 to the latest Eocene to earliest Oligocene. However, the middle Eocene to middle Miocene sedimentary section is very thin in the sites drilled by Leg 81 (Roberts, Schnitker et al., in preparation), precluding seismic differentiation of reflector R4 from overlying horizons and preventing a firm age correlation. Reflector R4 has not been unambiguously traced to boreholes drilled by Leg 80 in the Goban Spur region (de Graciansky, Poag et al., in preparation), and correlations there are speculative. Near Site 548 on the Goban Spur (Figs. 1,3), reflector R4 probably occurs at 0.41 sec on Challenger 48 and V28-04 profiles; assuming a seismic velocity of 1750 m/sec, reflector R4 correlates with a probable earliest Oligocene (~ 36.0 Ma) unconformity. At Site 551 reflector R4 occurs just below the seafloor; the uncored section here only constrains the age as pre-Pleistocene and post-middle Eocene. A very similar pattern of onlap onto reflector R4 by the post-R4 series can be seen at Site 551 and in the Hatton-Rockall Basin where reflector R4 and the post-R4 sequences are better defined (cf. Fig. 4 and Fig. 13). Reflector R4 probably occurs at 0.35 sec at Site 550; it correlates with the thin late Eocene to middle Oligocene section. At Site 549, reflector R4 probably lies at 0.14 sec, correlating with the latest Eocene to earliest Oligocene interval (38.0-36.0 Ma; assuming interval velocities between 1.5 and 2.0 km/sec).

Reflector terminations against oceanic basement dated with magnetic anomalies provide an independent, albeit crude, check on the age of the reflectors. Ruddiman (1972) noted the termination of reflector R4

against a crustal high on the Gardar Ridge (Iceland Basin; Fig. 1), which was dated as anomaly 13 (37.0 Ma on the time scale of Heirtzler et al., 1968; 35.5 Ma on the time scale of Hardenbol and Berggren, 1978). Use of the latter time scale would suggest that reflector R4 is somewhat younger than indicated from the borehole correlations discussed here. However, this apparent discrepancy may be resolved. In the Iceland Basin (Fig. 7), the pinchouts of reflector R4 occur between anomaly 13 and anomaly 21 (50.5 Ma, time scale of Hardenbol and Berggren, 1978). The terminations are closer to anomaly 13 than anomaly 21 (all magnetic anomaly identifications after Vogt and Avery, 1974). South of the Charlie-Gibbs Fracture Zone, reflector R4 also terminates between anomaly 13 and anomaly 21, while in the southern Labrador Sea reflector R4 terminates between anomalies 13 and 24. These terminations do not contradict the latest Eocene to earliest Oligocene age of reflector R4.

Correlations into Labrador Margin exploration wells suggest that horizon E/O (Fig. 15) is equivalent to reflector R4. Hinz et al. (1979) suggested that a lower reflector, horizon E, noted in the deep basin (Fig. 15) could be traced to the top of the Eocene in the Labrador Shelf exploration wells; horizon E would thus be the equivalent in age of reflector R4. However, examination of well logs, velocity logs, paleontological data, and seismic data (courtesy of F. Gradstein, S. Srivastava, A. Grant; Canadian Geological Survey) suggests that, due to problems in tracing horizons from the deep basin through the slope, it is equally likely that horizon E/O represents the top of the Eocene (Fig. 15). In the deep basin, horizon E pinches out between anomalies 27 and 28 (early Paleocene) on BGR 17 and BGR 21, and between anomalies 25 and 26 on BGR 12 (middle Paleocene); borehole correlations confirm that horizon E can be no older that early Eocene (Fig. 15). On BGR 17 (~ shotpoint 3500), horizon E/O merges with horizon U; it is believed that this is due to downlap of horizon U onto horizon E/O.[1] Horizon E/O

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[1] Hinz et al. (1979) showed that on profile BGR 17 horizon E merges with horizon U on their fig. 4, but that an overlying horizon (= E/O) merges with horizon U in their fig. 7; this discrepancy is due to mislabeling of horizon E on fig. 4 (S. Srivastava, personal communication).

cannot be traced on BGR 17, BGR21, and BGR 12 in the disturbed section between anomaly 24 and the extinct ridge axis; in fact, continuous reflectors generally cannot be traced through this zone (see also Le Pichon et al., 1971). Similarly, reflector R4 terminates against anomaly 24 in much of the southern Labrador Sea (anomalies identified after Srivastava, 1978). The similar pinchouts of reflector R4 and horizon E/O in the Labrador Sea support the contention that the two may be equivalent in age.

Reflectors R2 and R1

Roberts (1975) and Miller and Tucholke (in press; Appendix 3) noted that reflector R2 overlies the R3/R4 couplet in the Hatton-Rockall Basin (Fig. 4) and the southwest margin of Rockall Plateau (Fanghorn Drift; Fig. 14) (Table 1). Reflector R2 is an upper lower Miocene reflector at the upper boundary of silica-rich sediments (Fig. 2). Ruddiman (1972) noted a relatively continuous intermediate reflector (IR) above reflector R4 in the Iceland Basin. He dated this horizon as early Miocene (17 Ma or younger, based on the age of pinchout on oceanic crust), and attributed it to a change in abyssal circulation. This intermediate reflector (IR) therefore correlates in time with reflector R2. In the Iceland Basin, Reflector R2 (= IR) terminates against anomaly 5 on the profiles examined here, consistent with Ruddiman's interpretation and the age assignments for reflector R2 obtained from correlation to the boreholes (Fig. 2). Reflector R2 may correlate with a minor unconformity noted in the boreholes (Miller and Tucholke, in press; Appendix 3). The seismic interval between reflector R2 and the seafloor shows the most coherent pattern of current-controlled deposition in the northern North Atlantic in the form of prominent sediment drifts and associated sediment waves (Fig. 7). Sedimentation rates increased significantly in the Hatton-Rockall Basin and on the Fanghorn, Gardar, Hatton, and Eriador Drifts in the post-R2 interval (Table 1).

Roberts (1975) and Miller and Tucholke (in press; Appendix 3) noted that reflector R1 overlies reflector R2 in the Hatton-Rockall Basin (Fig. 4) and the southwest margin of Rockall Plateau. Reflector R1 falls

within upper Miocene calcareous chalks and may represent a lithification boundary (e.g., chalk/ooze) in the calcareous sediments. Along portions of the margin of Rockall Plateau (e.g., Sites 403-405; Fig. 2) deposition did not begin until R1 time (Fig. 2). Sedimentation rates increased in the Hatton-Rockall Basin and on the Fanghorn Drift in the post-R1 interval (Table 1).

The Abyssal Circulation Model

Reflector R4 occupies a chronostratigraphic position similar to Horizon A^u in the western North Atlantic. Stratal patterns associated with these reflectors are similar, i.e. truncation of deeper strata and the development of current-controlled deposition above. Thus, it is likely that both horizons had a similar cause: the development of vigorous bottom water circulation near the end of the Eocene (Miller and Tucholke, in press; Appendix 3).

Sediment distribution patterns provide evidence for a strong contour-following bottom water flow beginning at reflector R4 time. The widespread distribution of reflector R4 and its characteristic correlation with an unconformity (and similarly with Horizon A^u; Tucholke and Mountain, 1979) indicates that strong abyssal circulation affected the North Atlantic basins both east and west of the mid-ocean ridge beginning in the latest Eocene to earliest Oligocene. Along the margins of Rockall Plateau, the unconformity is especially well developed, demonstrating that topographic boundary effects probably intensified the abyssal circulation. The margin-intensified, anticlockwise circulation in the northeastern Atlantic was contained by the topographic barriers of the Rockall margin and the mid-ocean ridge (fig. 12 in Appendix 3). As a result, erosion and current-influenced deposition strongly affected the Porcupine/Biscay regions, despite the fact that these are regions of relatively quiescent bottom-water flow in the modern ocean. These erosional/depositional effects are reflected in a major unconformity noted in the Bay of Biscay/Goban Spur boreholes (Fig. 3) and in the development of the Porcupine Drift along the western margin of the Porcupine Abyssal Plain (Figs. 5,6). Further evidence of

post-R4 current-controlled, contour-following deposition is given by the post-R4 sediment isopach map for the Rockall region (Fig. 14). For abyssal circulation to have affected so strongly the sedimentary record in the Rockall region and in the Bay of Biscay, it is necessary that the eastern North Atlantic had a major source of bottom water.

The latest Eocene to earliest Oligocene abyssal circulation event associated with reflector R4 (and Horizon A^u) resulted from the influx of cold bottom water formed in polar-subpolar marginal basins of the North Atlantic. Several topographic features, the Mid-Atlantic Ridge, Azores-Gibraltar Ridge, Azores-Biscay Rise, and the Madeira-Tore Rise, probably prevented significant bottom water exchange between the northeastern North Atlantic and more southerly regions below ~ 3km (Miller and Tucholke, in press; Appendix 3). Although Schnitker (1980a,b) preferred Antarctic sources for Late Paleogene bottom water in the northern North Atlantic, it is unlikely that they could have been geologically significant even in the absence of these barriers, given the minor influence of Antarctic Bottom Water in this region today. Miller and Tucholke (in press; Appendix 3) speculated as to possible sources of the high-latitude, vigorously circulating bottom water: 1) Baffin Bay-Davis Strait; 2) formation of bottom water south of the Greenland-Scotland Ridge; and 3) overflow across the Greenland-Iceland Ridge (= nascent Denmark Straits) and/or across the Faeroe Bank Channel and Wyville-Thompson Ridge. Given the intensity of abyssal circulation in the northeast North Atlantic, especially the Rockall Trough, Porcupine Abyssal Plain, and Bay of Biscay, at least one source was probably overflow across the Wyville-Thompson Ridge. Miller and Tucholke (in press; Appendix 3) noted the time correlation between reflector R4 and the separation of Greenland and Spitsbergen (Talwani and Eldholm, 1977); they suggested that following the opening of this Arctic passage, Arctic waters rapidly entered the Norwegian-Greenland Sea, flowed through the Faeroe-Shetland Channel, across the Wyville-Thompson Ridge and entered the North Atlantic (see Chapter 4 for further discussion). The influx of this vigorously circulating bottom water resulted in strongly erosional conditions that lasted throughout much of the Oligocene (i.e. the R3-R4 interval).

A major early Miocene change in abyssal circulation (at the time of reflector R2) led to increased rates of deposition on the sediment drifts. Previous studies have suggested that increased deposition resulted from intensification of bottom water flow (e.g. Schnitker, 1980a,b; see discussion in Shor and Poore, 1979). In constrast, Miller and Tucholke (in press; Appendix 3) interpreted the change from widespread erosional condition prominent over the R3-R4 interval to coherent deposition of sediment drifts in the R2-R3 and especially in the post-R2 interval to be a result of a general decrease in intensity and stabilization of abyssal circulation. This interpretation is based on the fact that erosion of the major unconformity associated with reflector R4 required much higher current speeds, for speeds were above the limiting velocity separating erosion from deposition (see McCave and Swift, 1976, and references therein). Subsequently, speeds were reduced, resulting in the initiation of deposition above reflector R4.

The change from erosion to deposition above reflector R4 occurred progressively, with deposition beginning first in basins centers and beginning later toward basin margins. This is evidenced by: 1) deposition began in the early Oligocene in sites in the center of basins (e.g. Sites 116 and 112; Fig. 2); 2) deposition began in the middle Oligocene in sites closer to basin margins (about R3 time; e.g. Site 406); 3) deposition lagged until the middle to late Miocene in sites closest to the basin margins (e.g. Sites 403-405).

The progressive narrowing of the erosional zone and change to depositional conditions that occurred from early Oligocene through late Miocene is interpreted as representing a progressive decrease in the speed of abyssal currents. Increased rates of deposition on drifts in the middle Miocene (Table 1) may have resulted, in part, from increased sediment supply resulting in increasing concentration hence greater deposition (McCave and Swift, 1976). Such an increase in sediment supply to the basins may have resulted from lowered sea level in the late Oligocene to early Miocene (Vail et al., 1977). Nevertheless, decreased current velocities are necessary to explain the progressive change from sediment erosion and transport to deposition.

The general trend toward reduced bottom water flow was probably punctuated by brief but important erosional pulses resulting from intensified circulation. Examples of such erosional pulses include development of hiatuses in the latest early Miocene (about the time of reflector R2) and near the middle/late Miocene boundary (Figs. 2,3; fig. 5 in Appendix 3; fig. 3 in Shor and Poore, 1979). Tucholke and Laine (in press) noted two major erosional events in the Miocene of the western North Atlantic: a middle middle Miocene event (= Horizon X) and a middle/late Miocene event. Although the Horizon X event apparently post-dates the R2 erosional pulse, the timing of the middle/late Miocene event correlates between basins.

The overall interpretation of the development of abyssal circulation in the North Atlantic is: 1) a rapid increase in current strength occurred during the latest Eocene to early Oligocene, creating strongly erosional conditions; 2) a general decrease in intensity of flow occurred during the Oligocene to early Miocene, resulting in increased coherence of deposition; and 3) a further decrease and stabilization of abyssal flow occurred in the middle to late Miocene; coherent development of sediment drifts has continued more or less unaltered from this time to the present (see figs. 12a-12c in Appendix 3). This long-term trend in the development of abyssal circulation in the North Atlantic was probably punctuated by the minor erosional pulses such as those discussed above. In addition, other climatic events such as the initiation of northern hemisphere glaciation (~ 2.5-3 Ma; Berggren, 1972) and the intensification of glaciation beginning about one million years ago (Shor and Poore, 1979; Prell, 1980) severely affected the lithostratigraphic record of the northern North Atlantic (Davies and Laughton, 1972). The relationships among abyssal circulation, tectonic, and climatic histories of the North Atlantic will be discussed under paleoceanographic synthesis (Chapter 4).

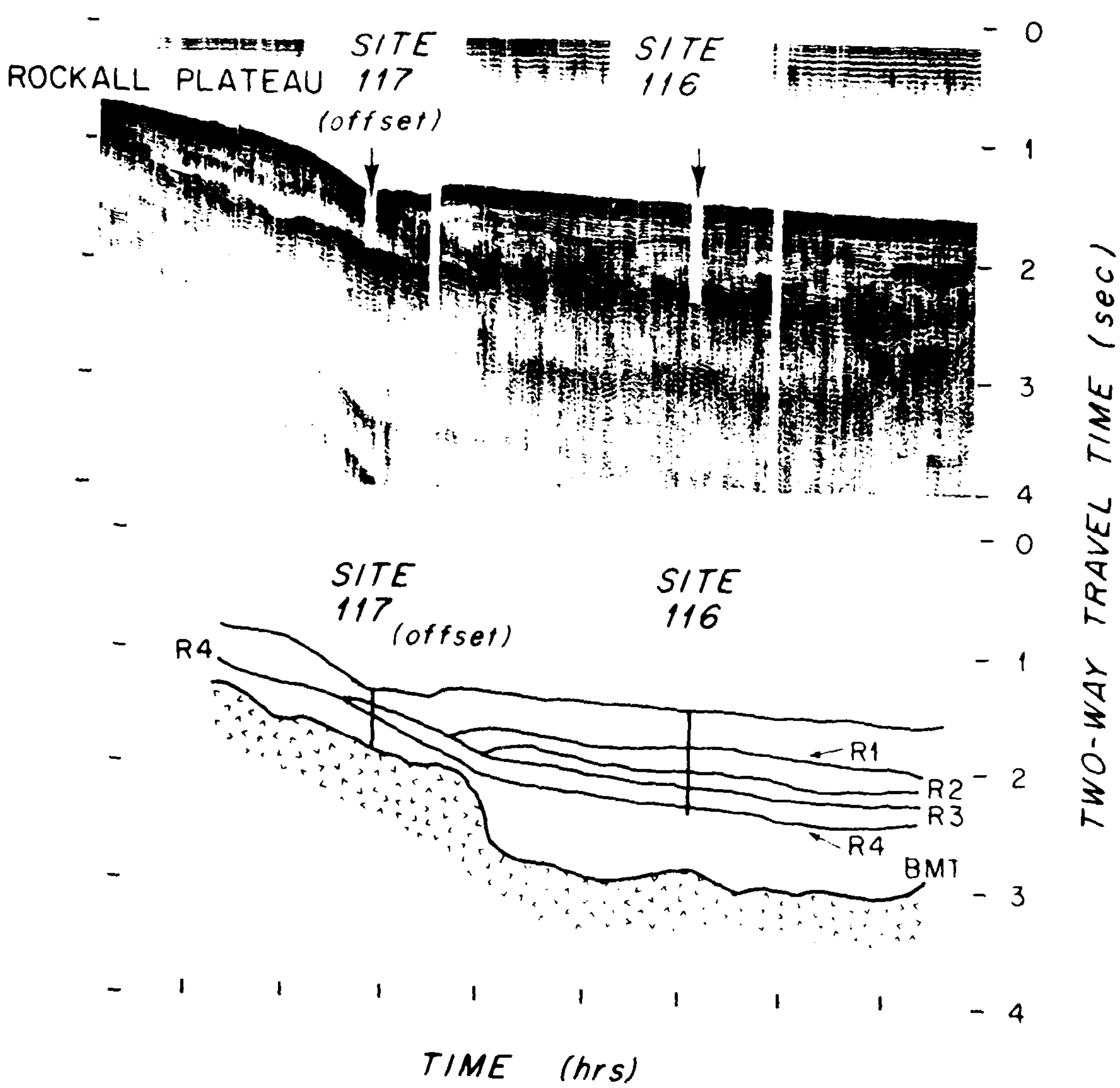


Figure 4. Seismic reflection profile and interpretation of profile V28-04 across DSDP Sites 116 and 117, Hatton-Rockall Basin. Located in Figure 1 as section G. Reflector R4 is upper Eocene to lowermost Oligocene; reflector R3 is middle to upper Oligocene; reflector R2 is uppermost lower Miocene; reflector R1 is upper Miocene. In this and subsequent figures, basement indicated is undifferentiated acoustic basement. After Miller and Tucholke (in press).

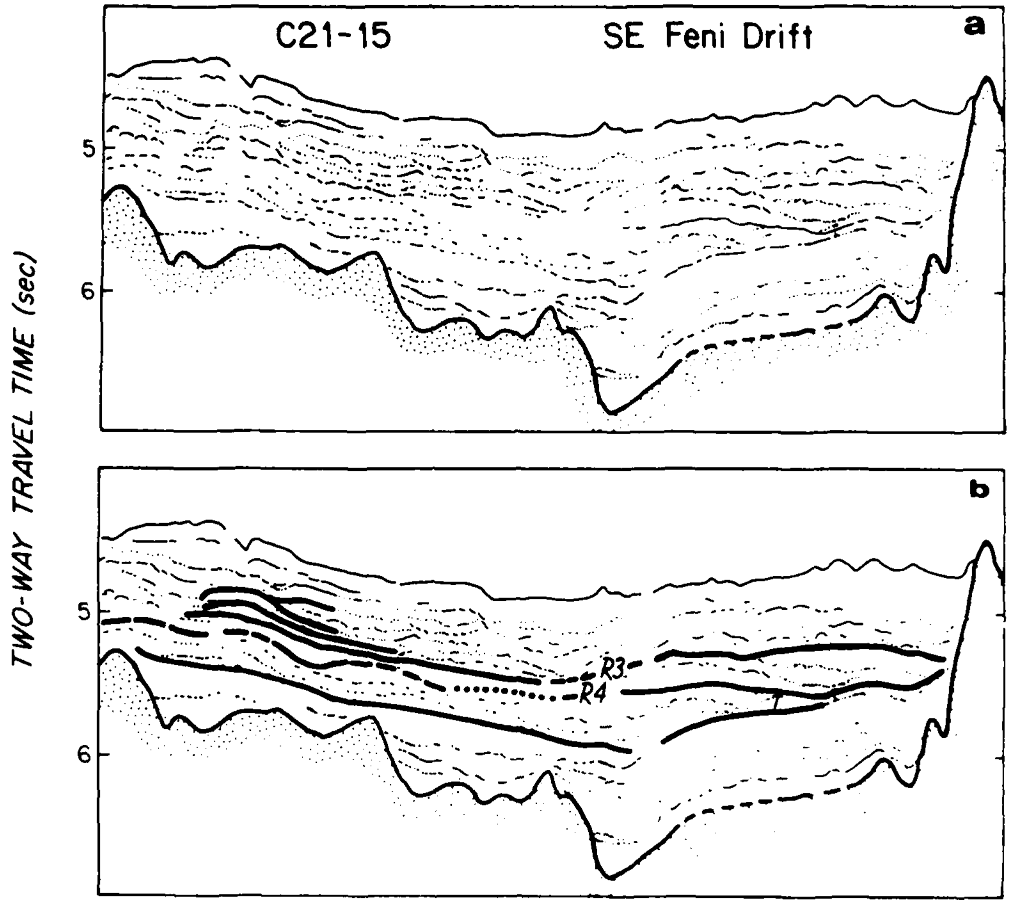


Figure 5. Tracing (part A at top) and interpretation (part B on bottom) of profile C21-15 across the SE Feni Drift. Located in Figure 1 as section I.

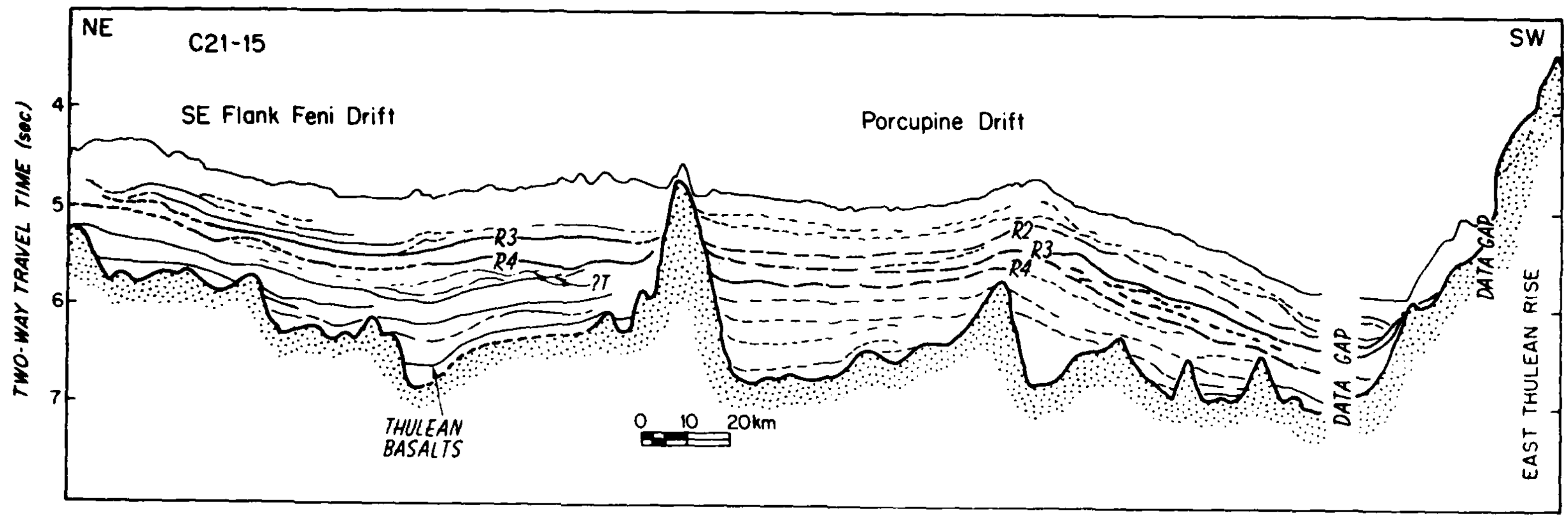


Figure 6. Interpretation of profile C21-15 across the SE Feni Drift and a drift in the eastern Porcupine Abyssal Plain. Located in Figure 1 as section I. NE portion of this line is given in Figure 5. T = truncation of pre-R4 reflectors by reflector R4.

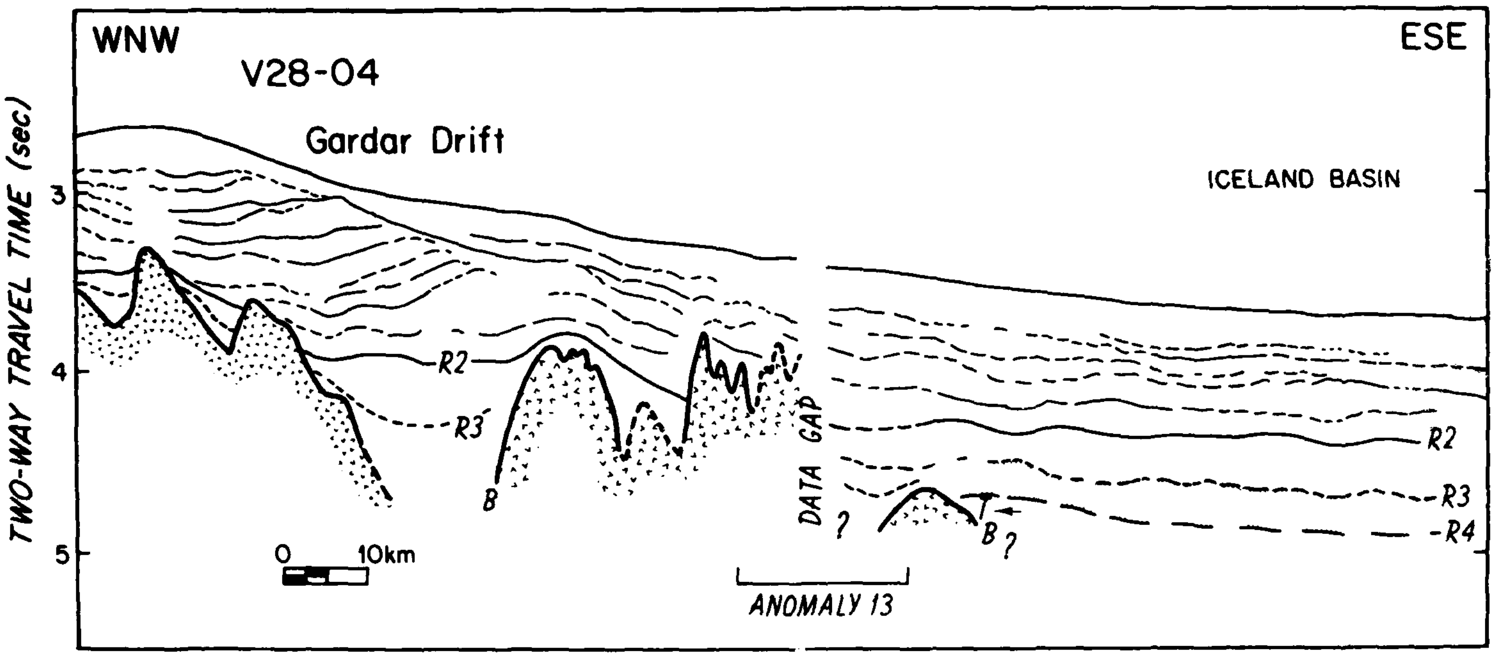


Figure 7. Interpretation of profile V28-04 across the Gardar Drift. Located in Figure 1 as section E. Reflectors R3 and R4 are poorly defined in original data. Note development of large waveforms in the post-R2 interval. Position of anomaly 13 is approximate, and follows Vogt and Avery (1974). T = termination of reflector R4. B = basement.

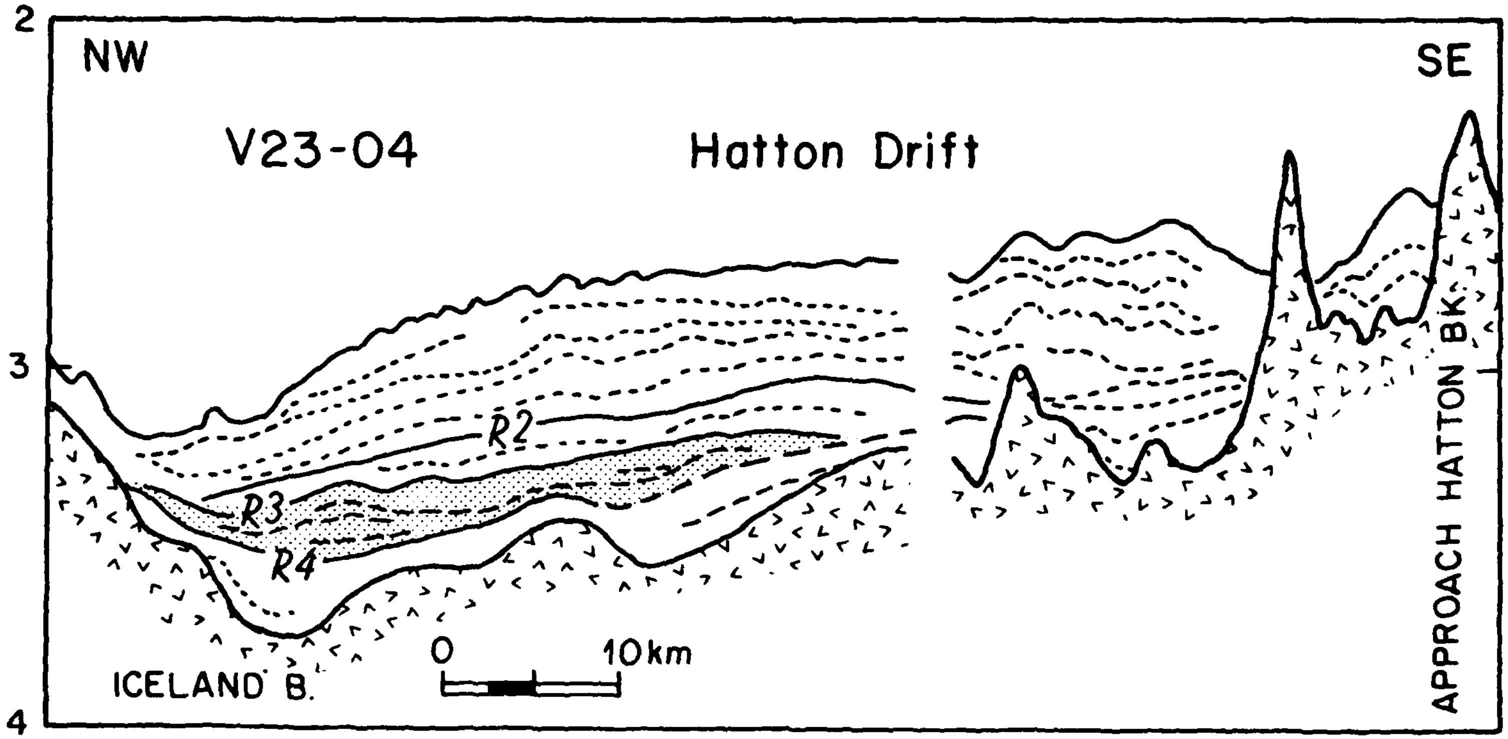


Figure 8. Interpretation of profile V23-04 across the Hatton Drift. Located in Figure 1 as section F.

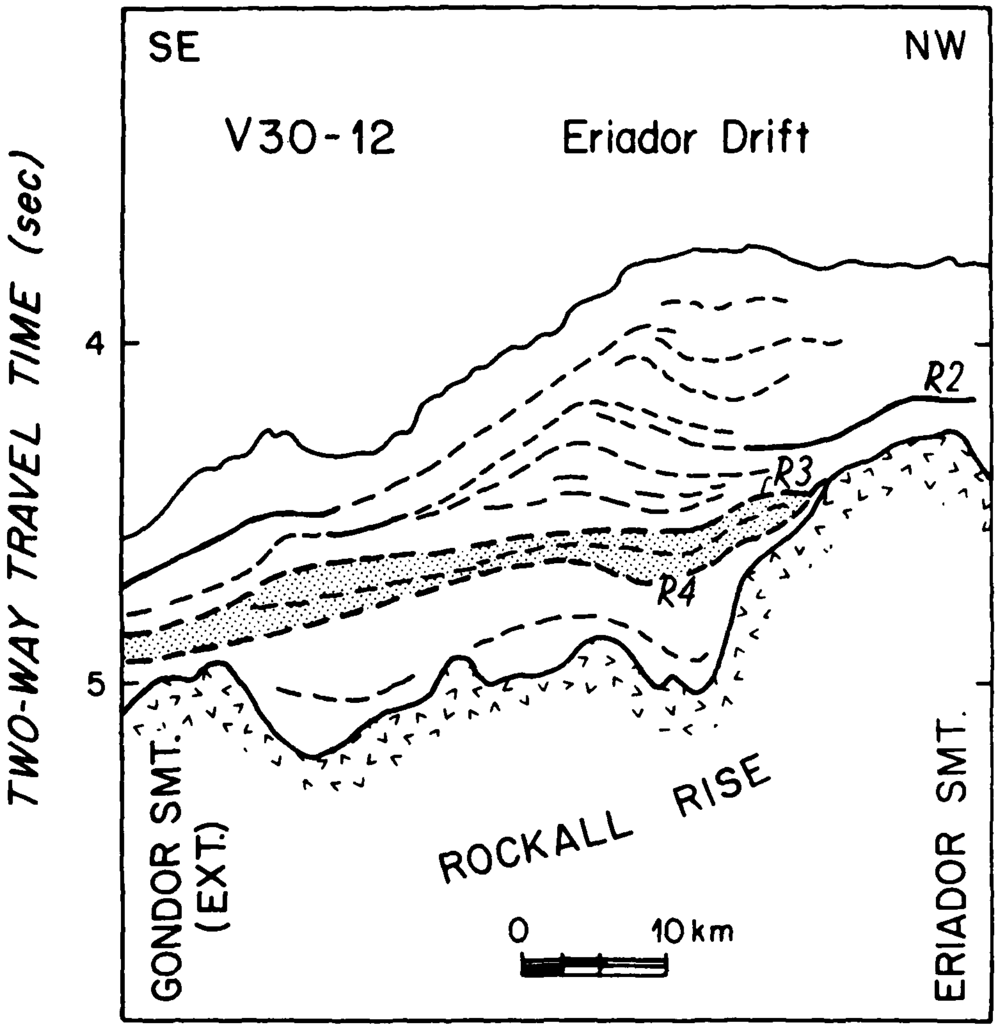


Figure 9. Interpretation of profile V30-12 across a drift developed on the flank of Eriador Seamount. Located in Figure 1 as section H.

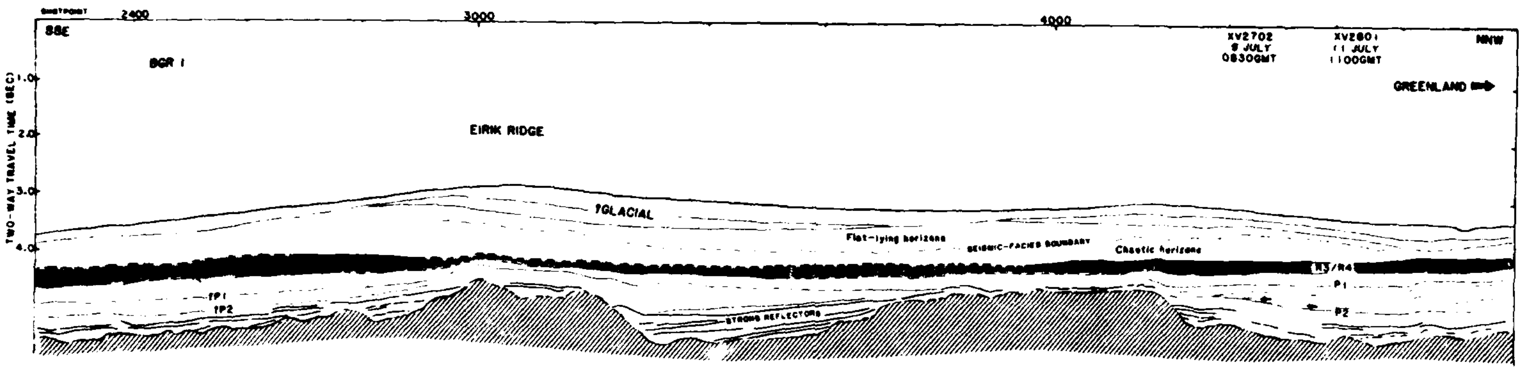


Figure 10. Interpretation of multichannel profile BGR 1 across the Eirik Drift. Located in Figure 1 as section C. Data provided by S. Srivastava and K. Hinz.

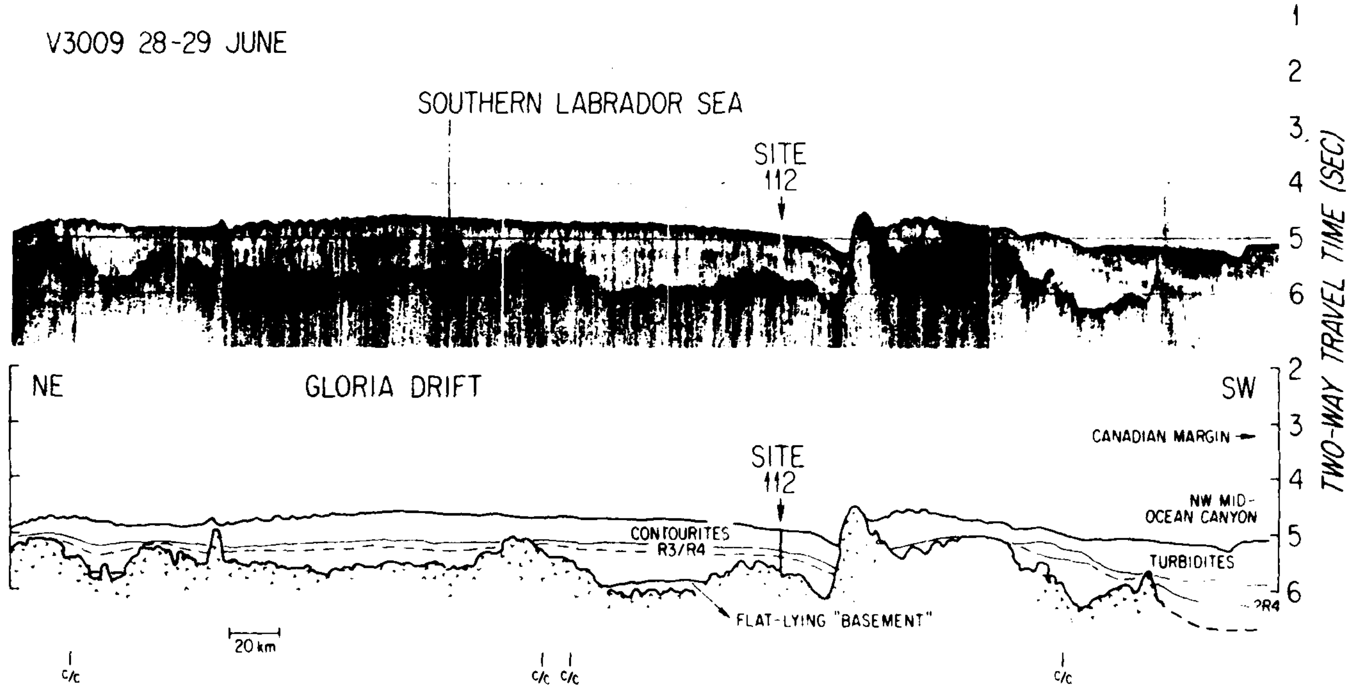


Figure 11. Seismic reflection profile and interpretation of profile V30-09 across DSDP Site 112 on Gloria Drift. Located in Figure 1 as section D.

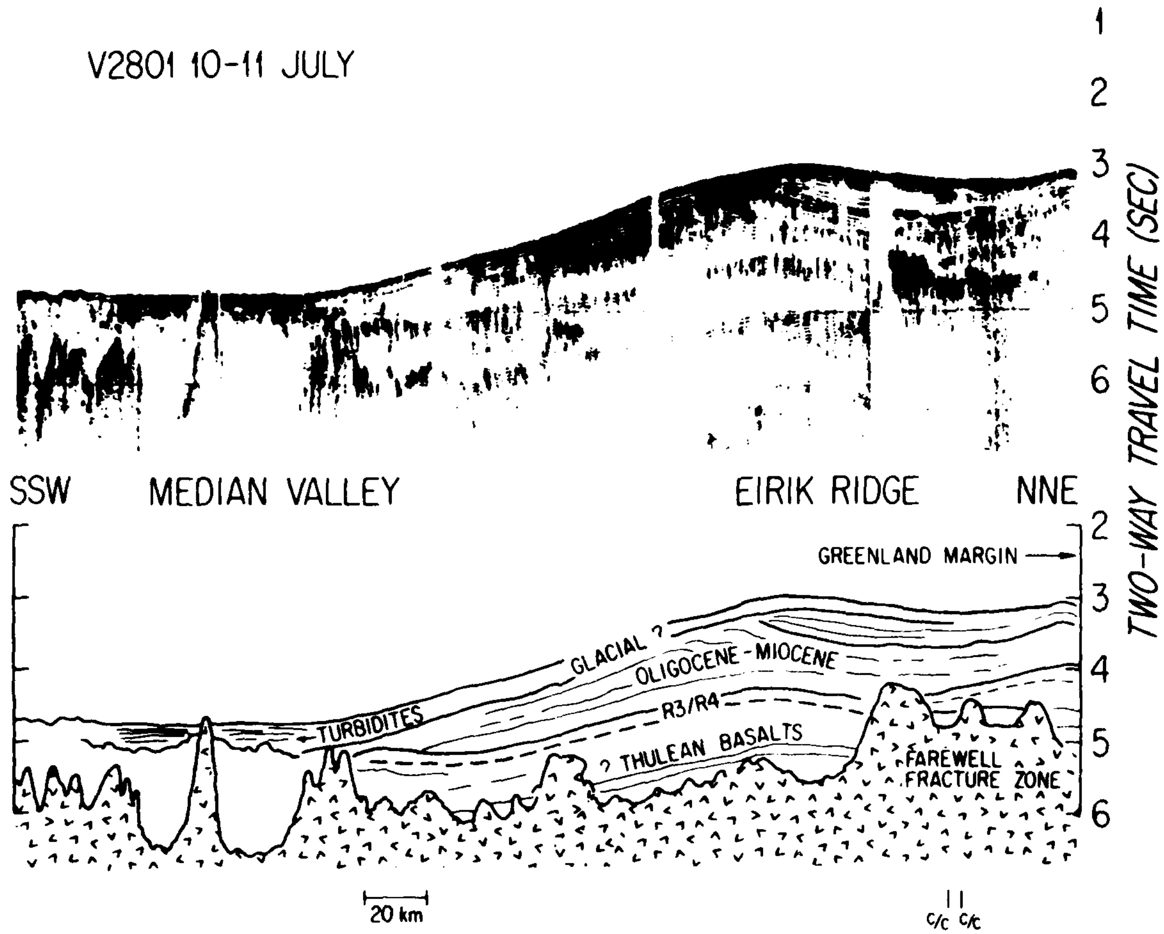


Figure 12. Single channel seismic reflection profile and interpretation of profile V28-01 across the Eirik Drift. Located in Figure 1 as section B.

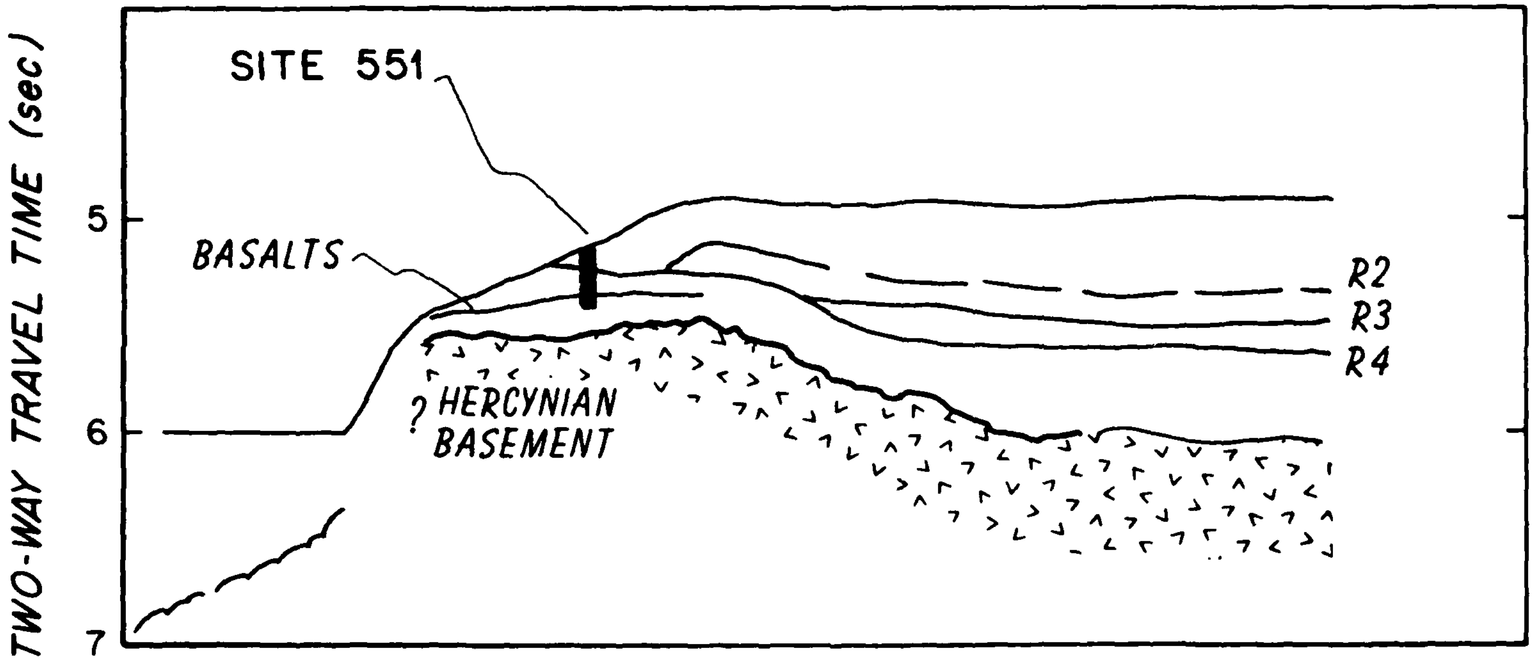


Figure 13. Interpretation of profile through Site 551. Located in Figure 1 as section J. Data provided by C.W. Poag and P.C. de Graciansky.

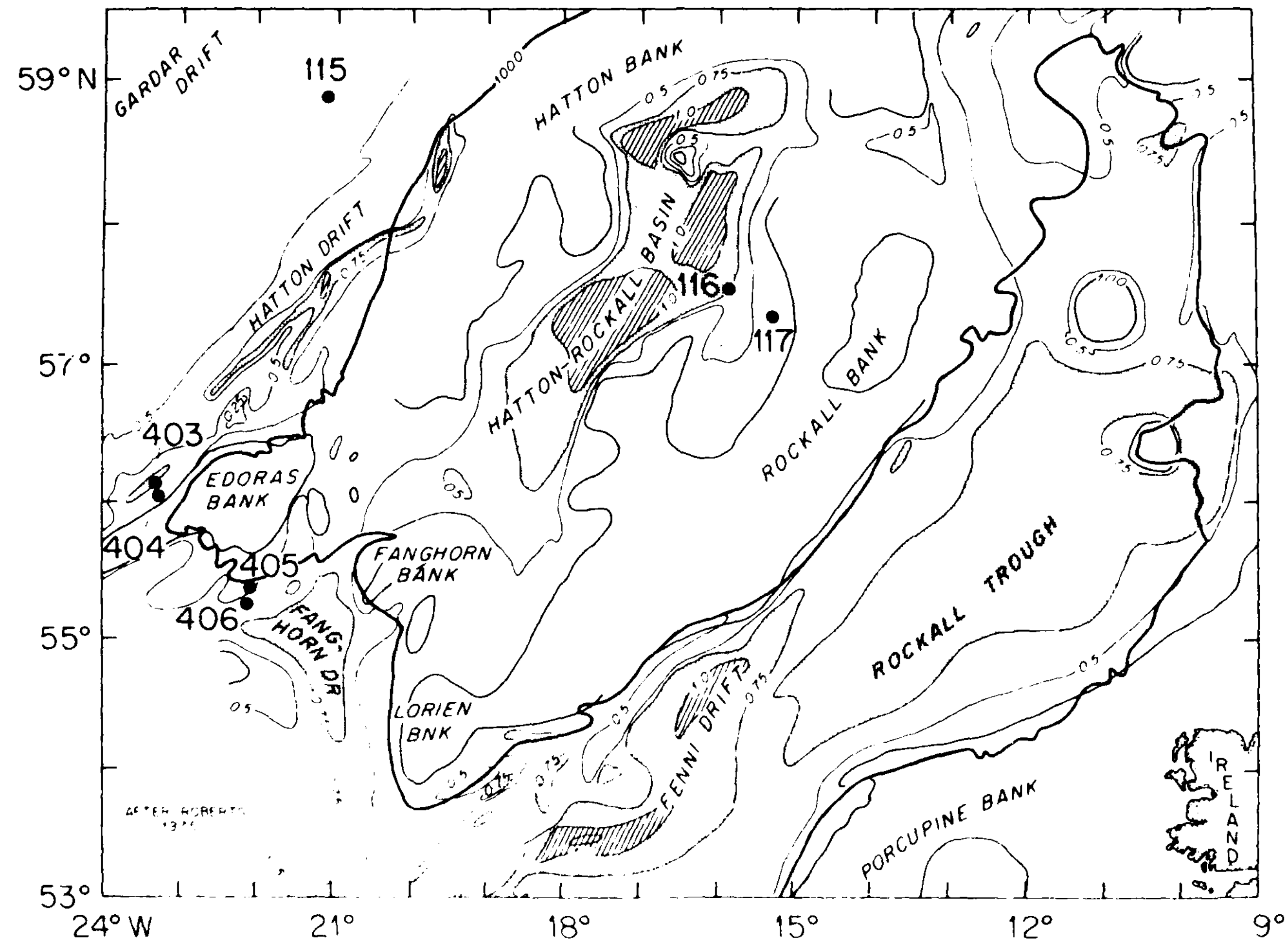


Figure 14. Post-R4 sediment thickness (in seconds two-way travel time) of the Rockall Plateau and environs showing location of DSDP sites. Modified after Roberts (1975).

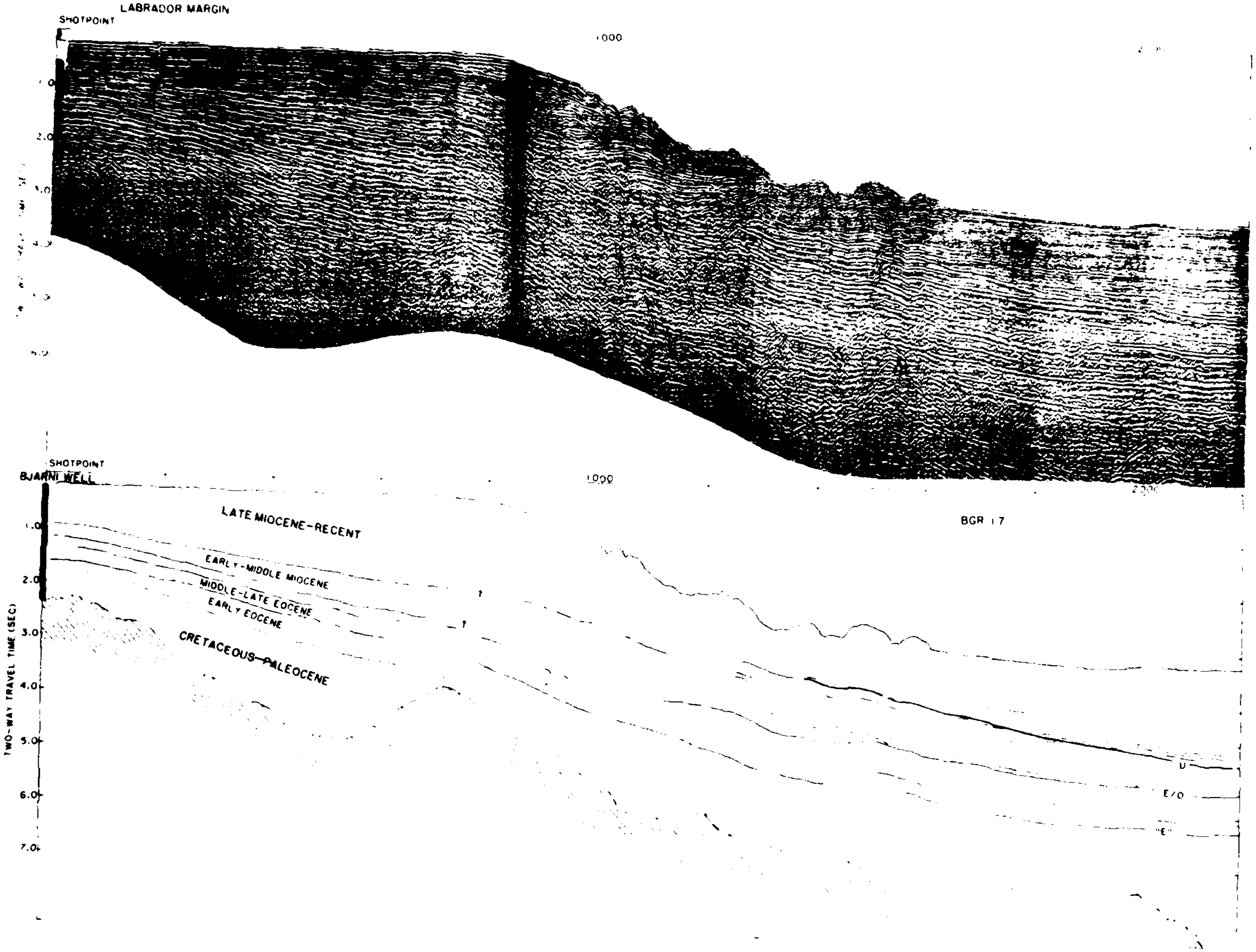


Figure 15. Multichannel seismic reflection profile and interpretation of profile BGR 17 across the Labrador Margin into the southern Labrador Sea. Bjarni well age assignments after Gradstein and Williams (1981). Data after Hinz et al. (1979).

CHAPTER 3: RELATIONSHIPS AMONG FAUNAL, ISOTOPIC, AND ABYSSAL CIRCULATION CHANGES

The distribution patterns of modern deep-sea benthic foraminifera often correlate with water masses and properties that co-vary with water masses (Streeter, 1973; Schnitker, 1974; Lohmann, 1978; Corliss, 1979a; Bremer and Lohmann, in press). Interpretations of water-mass/foraminiferal relationships have been extended to the Tertiary fossil record in order to infer changes in paleocirculation (Schnitker, 1979; Tjalsma and Lohmann, in press; Douglas and Woodruff, 1981). However, paleoceanographic interpretations of changes in deep-sea benthic foraminiferal assemblages often conflict. This is illustrated by disputes as to the nature, timing, and causes of Late Paleogene benthic foraminiferal changes. Douglas (1973), Boersma (1977), and Schnitker (1979) suggested that a major benthic foraminiferal turnover occurred near the Eocene/Oligocene boundary, while Corliss (1979b, 1981), Tjalsma (1982), and Tjalsma and Lohmann (1982) suggested more gradual, sequential changes. Benthic foraminiferal assemblage data from both the Miocene (Schnitker, 1979, 1980a,b) and the Late Paleogene (Appendixes 1,4,5) have been cited as evidence for the first significant influx of bottom water into the North Atlantic from northern sources (Arctic and/or Norwegian-Greenland Sea). The seismic stratigraphic record provides less ambiguous evidence for changes in abyssal circulation than can be inferred from benthic foraminiferal assemblage data. Benthic foraminiferal isotopic evidence can provide valuable supportive evidence of changes in abyssal circulation; this evidence can be used to evaluate and expand upon the abyssal circulation model developed from seismic stratigraphic studies (Chapter 2; Appendix 3). Late Paleogene benthic foraminiferal changes in the North Atlantic are used to interpret possible changes in water masses; the interpretations obtained from such water mass-foraminiferal relationships are evaluated in view of changes in abyssal circulation circulation inferred from the seismic stratigraphic and isotopic studies.

A major latest Eocene to earliest Oligocene enrichment of benthic foraminiferal ^{18}O had been noted previously from the Southern and

Pacific Oceans (Shackleton and Kennett, 1975; Savin et al., 1975; Kennett and Shackleton, 1976; Keigwin, 1980). Such ^{18}O enrichments may possibly represent a global change in the isotopic composition of seawater or a drop in bottom-water temperature or both. Initial studies suggested that the major buildup of continental ice in the Tertiary did not occur until the middle Miocene, and therefore, that the enrichment near the Eocene/Oligocene boundary must represent a major cooling (Shackleton and Kennett, 1975; Savin et al., 1975; Kennett and Shackleton, 1976; Savin, 1977). Matthews and Poore (1980), on the other hand, suggested that the enrichment may represent the first major buildup of continental ice on Antarctica.

Prior to the studies conducted here (Appendixes 2,5), it was believed that the major enrichment of ^{18}O occurred near the middle/late Eocene boundary in the North Atlantic at Sites 400A and 398 (Fig. 1) (Vergnaud-Grazzini et al., 1978, 1979; Vergnaud-Grazzini, 1979). Miller and Curry (1982; Appendix 2) analyzed oxygen and carbon isotopic composition of benthic foraminifera from Sites 119 and 401 (Fig. 16). They found that $\delta^{18}O$ values increased ~ 1.9 $^{o}/oo$ and $\delta^{13}C$ values increased ~ 0.8 $^{o}/oo$ between the early middle Eocene (Zones NP13-NP15) and the earliest Oligocene (Zone NP21) of Site 119. They combined isotopic records for Sites 119 and 401 and concluded that ~ 1.4 $^{o}/oo$ of the $\delta^{18}O$ increase occurred in the late Eocene to earliest Oligocene (Fig. 17). They could not resolve biostratigraphically the exact timing of the enrichment, which may have occurred over a period of less than one million years (within Zone NP21) or as long as 4 million years (between Zones P15 and NP21). Miller and Curry suggested that the low Eocene benthic foraminiferal $\delta^{18}O$ values at Sites 400A and 398 (as much as 2 $^{o}/oo$ lower than at Sites 119 and 401) resulted from diagenetic alteration of foraminiferal tests in these more deeply buried sites (see Vergnaud-Grazzini et al. (1978, 1979), Vergnaud-Grazzini (1978), Renard et al. (1979a, 1979b), and Arthur et al. (1979) for evidence of diagenetic alteration of the Eocene sections at these sites).

Miller et al. (in press; Appendix 5) examined the $\delta^{18}O$ record of Site 549 on the Goban Spur (Fig. 17). Site 549 is the first North Atlantic DSDP site with continuous recovery of well-dated upper Eocene

through lower Oligocene sediments, apparently unaltered by diagenetic or dissolution effects. This record allows a firm determination of isotopic changes across the Eocene/Oligocene boundary. Here, a major $\delta^{18}O$ increase began at ~ 38 Ma (late Eocene) and culminated in a rapid (< 0.5 my) increase in $\delta^{18}O$ just above the Eocene/Oligocene boundary (~ 36.5 Ma)(Fig. 17). Miller et al. (in press; Appendix 5) established that the ^{18}O enrichment correlates with an enrichment noted by Keigwin (1980) from the Southern and Pacific Oceans. Assuming that the extinctions of the planktonic foraminifera used to recognize the Eocene/Oligocene boundary (viz. Hantkenina, Cribrohantkenina, and Globorotalia cerroazulensis) are synchronous, the ^{18}O enrichment is a chronostratigraphic marker. Whether this enrichment is attributable to ice-volume buildup or to a temperature decrease of bottom waters, remains in debate. Keigwin argued that the $\delta^{18}O$ increase in benthic foraminifera represented mostly a temperature decrease because of the lack of covariance of the enrichment in planktonic and benthic foraminifera at tropical Site 292 (Phillipine Sea). Assuming buildup of glacial ice from an ice-free Eocene world to a fully-glaciated Oligocene world (with ice volume equal to present-day ice volume), Miller and Curry (1982; Appendix 2) argued that an excess $\delta^{18}O$ increase remains, representing at least a $2^{o}C$ temperature drop. Thus, even if the enrichment reflects ice-volume buildup, a temperature drop of bottom water must have occurred in the latest Eocene to earliest Oligocene.

A rapid major $\delta^{13}C$ increase correlates with the earliest Oligocene $\delta^{18}O$ increase at Site 549 (fig. 3 in Appendix 5). A similar drop occurs in the composite Site 119/401 record (fig. 2 in Appendix 2). Since these records differ from those of Keigwin (1980), they probably cannot be attributed to global changes in $\delta^{13}C$; rather, the $\delta^{13}C$ increases were interpreted as reflecting a decrease in the age of bottom water. Such a decrease in age would have resulted in increased O_2, decreased CO_2, increased pH, and bottom waters less corrosive to calcium carbonate (Miller and Curry, 1982; Miller et al., in press; Appendixes 2,5). Distinct minima of $\delta^{13}C$ occur in the middle Eocene and middle Oligocene of Site 119 (Fig. 16), and were interpreted as reflecting older (high CO_2 and low pH, hence more corrosive) bottom water.

Faunal studies of northern North Atlantic sites indicate that major benthic foraminiferal changes occurred at abyssal depths between the middle Eocene and the earliest Oligocene (Miller et al., 1982; Miller, in press b; Appendixes 1,4). In the deep southern Labrador Sea, Eocene predominantly agglutinated assemblages are replaced by an early Oligocene calcareous assemblage; lithology, percent carbonate, and percent carbon are relatively constant across the faunal change (fig. 5 in Appendix 1). Miller et al. (1982; Appendix 1) suggested that certain hydrographic properties (viz. low O_2, low pH, high CO_2, more corrosive waters) promote the development of predominantly agglutinated benthic foraminiferal assemblages, and attributed the change in assemblages in the Labrador Sea to a decrease in age of bottom waters resulting from the influx of northern bottom water. Unfortunately, coring gaps prevented establishing the exact timing of this faunal change.

A major faunal change in calcareous benthic foraminifera also occurred between the early middle Eocene and earliest Oligocene at two abyssal (> 3 km paleodepth) sites in the Bay of Biscay (Sites 119 and 400A; in the > 150 μm size-fraction)(Miller, in press b; Appendix 4; Schnitker, 1979). *Nuttallides truempyi*, *Clinapertina* spp., and *Abyssamina* spp., which dominated the Eocene abyssal benthic assemblage, were replaced by increasingly abundant, bathymetrically wide-ranging and stratigraphically long-ranging taxa: *Oridorsalis* spp., *Globocassidulina subglobosa*, *Gyroidinoides*, and the *Cibicidoides ungerianus* plexus (Figs. 18,19). Many abyssal taxa became extinct prior to the early Oligocene. However, a late Eocene hiatus encountered at Sites 119 and 400A prevents dating the timing of these extinctions (Figs. 18,19).

Eocene to early Oligocene benthic foraminiferal assemblage changes are well defined at Site 549 (Miller et al., in press; Appendix 5). At Sites 549 (~ 2.0-2.5km paleodepth), the major faunal change is the replacement of the *Nuttallides truempyi* assemblage just above the middle/late Eocene boundary (Fig. 20); this event can be shown to have occurred throughout the North Atlantic, South Atlantic, Caribbean, and Gulf of Mexico at this time (figs. 10,11 in Appendix 5; Tjalsma and Lohmann, in press). Other faunal changes at Site 549 include 1) a series of extinctions and local last appearances of taxa in the late Eocene; 2)

a series of first appearances (some of which are local) in the late Eocene to earliest Oligocene; and 3) the replacement of a buliminid assemblage just below the Eocene/Oligocene boundary (Fig. 20). The record at Site 549 firmly established that no major benthic foraminiferal changes (in the > 150 μm size fraction) are associated with the Eocene/Oligocene boundary in the North Atlantic; instead, benthic foraminiferal changes occurred throughout the late Eocene to earliest Oligocene interval (~ 40-36 Ma). Many of the first and last appearances and the replacement of the buliminid assemblage are probably local phenomena; however, the decrease in abundance and extinction of N. truempyi and associated abyssal taxa represent a dramatic benthic foraminiferal change that occurred throughout the Atlantic Ocean (Tjalsma and Lohmann, in press; Miller in press b; Miller et al., in press; Appendixes 4,5). In the evolution of deep-sea benthic foraminifera during the Cenozoic, only the massive extinctions of the latest Paleocene (Tjalsma and Lohmann, in press) and assemblage changes of the middle and late Miocene (Douglas and Woodruff, 1981) rival changes that occurred between the middle Eocene and the early Oligocene in importance.

Major benthic faunal changes also occurred in the Late Paleogene in ostracodes. Between the middle Eocene and the early Oligocene, the modern cold-water ostracode fauna developed; this was attributed to the development of cold bottom water circulation and the associated development of the oceanic cold-water sphere (= psychrosphere)(Benson, 1975). Ducasse and Peypouquet (1979) similarly noted that the psychrospheric ostracode fauna appeared in the late Eocene at Site 406 (SW margin of Rockall Plateau). The exact timing of the change in ostracodes is debatable (cf. Benson, 1975 with Corliss, 1981); however, it is clear that between the middle Eocene and the early Oligocene benthic faunas, both ostracodes and foraminifera, underwent a major reorganization.

The relationships of the Eocene to early Oligocene benthic foraminiferal isotopic and assemblage changes are well defined at Site 549. The late Eocene faunal changes began ~ 39.5 Ma, prior to the 1 $^{0}/oo$ oxygen isotopic enrichment which occurred between ~ 38.5 and 36.5 Ma (late Eocene to earliest Oligocene). Although several extinctions and

local last appearances occurred in the late Eocene to earliest Oligocene, the majority of taxa range through the Eocene to Oligocene temperature drop.

With the resolution provided at Site 549, the changes in faunal isotopic and assemblage composition can be compared with the abyssal circulation model. The change from sluggish to vigorous, intense bottom water circulation associated with reflector R4 occurred in the late Eocene to earliest Oligocene (Miller and Tucholke, in press; Appendix 3; Chapter 2). Because of the uncertainties in assigning an age to reflector R4, the erosional event associated with this reflector may be coincident with either the early late Eocene assemblage change or the latest Eocene to earliest Oligocene isotopic changes. Still, reflector R4 is probably latest Eocene to earliest Oligocene (~ 36-38 Ma) (see Chapter 2 for discussion), although uncertainties in the biostratigraphy and the correlation of reflector R4 into the various boreholes prevent absolutely establishing this. If this age assignment is correct, reflector R4 and the associated major abyssal circulation change correlate with the major ^{18}O enrichment, but they post-date the initial faunal changes.

The diachrony of the major faunal change with the isotopic and seismic stratigraphic changes poses a problem. An explanation may be provided by considering the overall development of Cenozoic deep-sea benthic foraminiferal assemblages. The major Late Paleogene faunal changes are the progressive restriction of abyssal Eocene taxa to greater depths and the ultimate extinction of these abyssal taxa, *Nuttallides truempyi*, *Clinapertina* spp., *Abyssammina* spp., *Alabamina dissonata*, and *Aragonia* spp. (Tjalsma and Lohmann, in press; Miller, in press b; Appendix 4). The depth-restriction apparently began in the middle Eocene, climaxing in the replacement of the abyssal Eocene taxa just above the middle/late Eocene boundary (40-38 Ma)(Tjalsma and Lohmann, in press; Miller et al., in press; Appendix 5). In addition, several species important in the modern abyssal ocean (e.g. *Nuttallides umbonifera*, *Epistominella exigua*, *Eggerrella bradyi*) made their appearance in the late Eocene to early Oligocene (Miller, in press b; Miller et al., in press; Appendixes 4,5). These changes represent the

transition from assemblages dominated by Cretaceous and Paleocene relict taxa (Tjalsma and Lohmann, in press) toward the development of modern benthic foraminiferal assemblages. Although they occur at intermediate (e.g. Sites 549 and 401; 2.0-2.5km paleodepth) and shallower (e.g. Site 548; ~ 1km paleodepth) sites, these changes are most dramatic at deepest sites (e.g. Sites 119, 400A, 550; all > 3km paleodepth; Miller, in press b; Miller et al., in press; Appendixes 4, 5). In fact, intermediate-depth Eocene assemblages are very similar in abundance composition (with the exception of abundant Nuttallides truempyi in the Eocene) to deep Oligocene assemblages (Schnitker, 1979; Miller, in press b; Appendix 4), with dominant Globocassidulina subglobosa, Gyroidinoides spp., Cibicidoides ungerianus, and Oridorsalis umbonatus. These taxa are bathymetrically wide-ranging and stratigraphically long-ranging, and may be interpreted as tolerant of environmental changes.

I speculate that the abyssal Late Paleogene fauna (Nuttallides truempyi and associated Clinapertina spp., and Abyssammina spp., Alabamina dissonata, Aragonia spp.) was adapted to the warm, corrosive, older bottom waters of the Eocene. The deep-sea environment began to change gradually in the middle to late Eocene, resulting in their demise. This paleoenvironmental change may be due to climatic cooling resulting in cooling of bottom waters, leaking of bottom waters from the Norwegian-Greenland Sea or Arctic Ocean, or other as yet undetermined causes. Circumstantial evidence of paleoenvironmental changes include a $\delta^{13}C$ increase of ~ 0.6 $^{o}/oo$ that correlates with the replacement of the N. truempyi assemblage (Miller et al., in press; Appendix 5) and a general cooling of bottom waters that began in the middle Eocene (Shackleton and Kennett, 1975). As a result of these initial paleoenvironmental changes, the Eocene abyssal fauna was replaced by Globocassidulina subglobosa, Gyroidinoides spp., Cibicidoides ungerianus, and Oridorsalis umbonatus. These taxa increased in abundance to form the nucleus of the abyssal late Eocene fauna. Since these taxa probably had wide environmental tolerances, they were not seriously affected by the culmination of the paleoceanographic changes near the Eocene/Oligocene boundary, viz. the rapid bottom water temperature drop, increased intensity of bottom water circulation, and decrease in the age of bottom

water (higher O_2, lower CO_2, higher pH, hence less corrosive).

In the Bay of Biscay, Globocassidulina subglobosa, Gyroidinoides spp., Cibicidoides ungerianus, and Oridorsalis umbonatus continue to dominate in the early Oligocene at both intermediate (~ 2km) and deep (> 3km) sites. Subsequently in the middle Oligocene, Nuttallides umbonifera expands in abundance in the deepest sites in the northern North Atlantic (> 3 km; Sites 119, 400A, 550), becoming the dominant benthic foraminifera (Fig. 16). In the modern oceans, the abundance of N. umbonifera is positively correlated with increased corrosiveness of bottom water (Bremer and Lohmann, in press); at Site 119 the greatest abundances of Nuttallides spp. are associated with the lowest $\delta^{13}C$ values in benthic foraminifera (Fig. 16) (Miller and Curry, 1982; Appendix 2). Lower $\delta^{13}C$ values are often associated with older water masses that are, in turn, more corrosive to carbonate (Kroopnick et al., 1972; Kroopnick, 1974, 1980; Lohmann and Carlson, 1981) Thus, the middle Oligocene of Site 119 was interpreted as reflecting older, more corrosive bottom water (Miller and Curry, 1982; Miller, in press b; Appendixes 2,4). This suggested increase in age and corrosiveness correlates with a general reduction of intensity of abyssal circulation associated with the post-R3 depositional pulse.

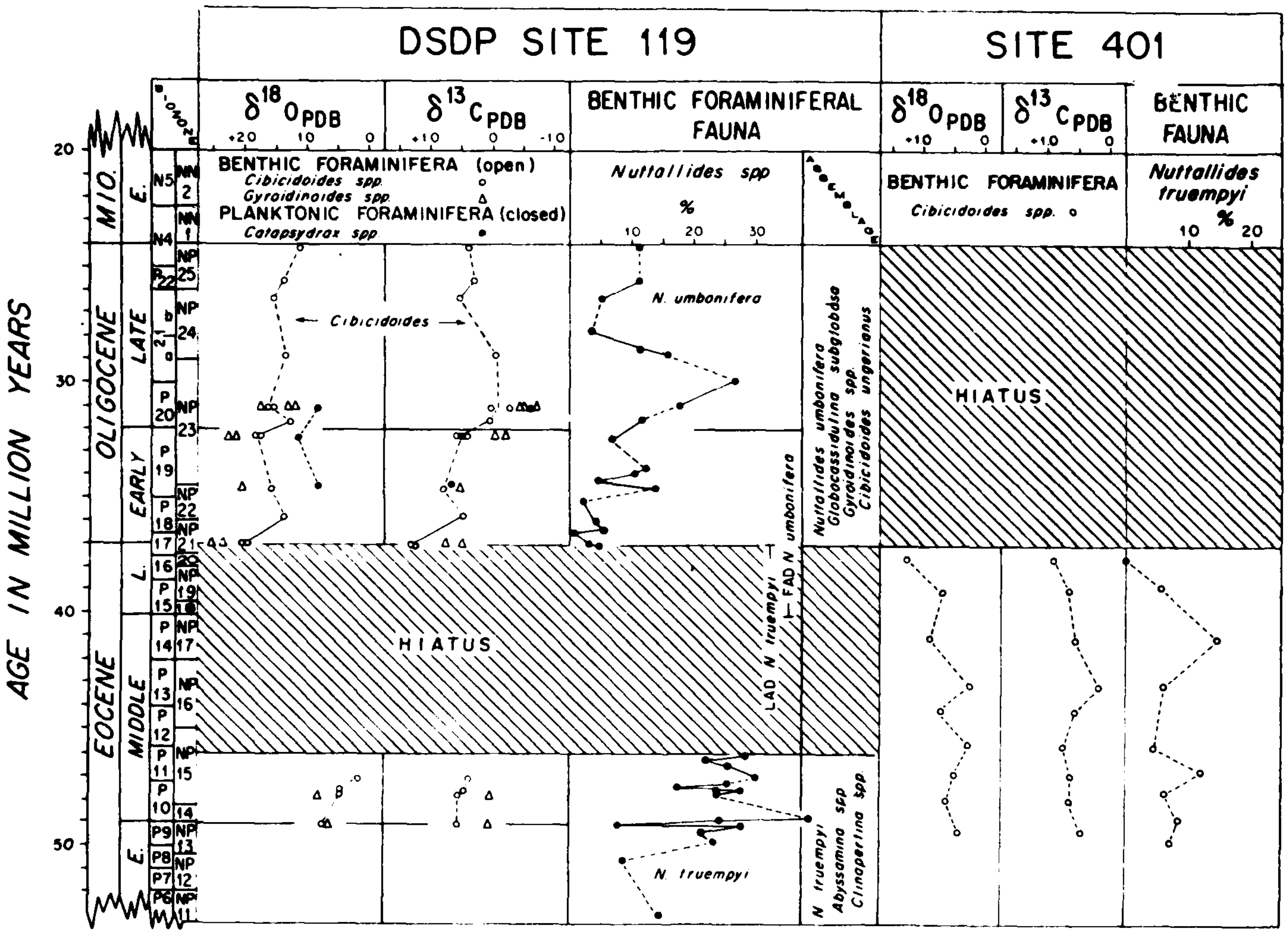


Figure 16. Isotopic composition and distribution of Nuttallides spp. at Sites 119 and 401 in the Bay of Biscay. Site location given in Figure 1. After Miller and Curry (1982) and Miller (in press).

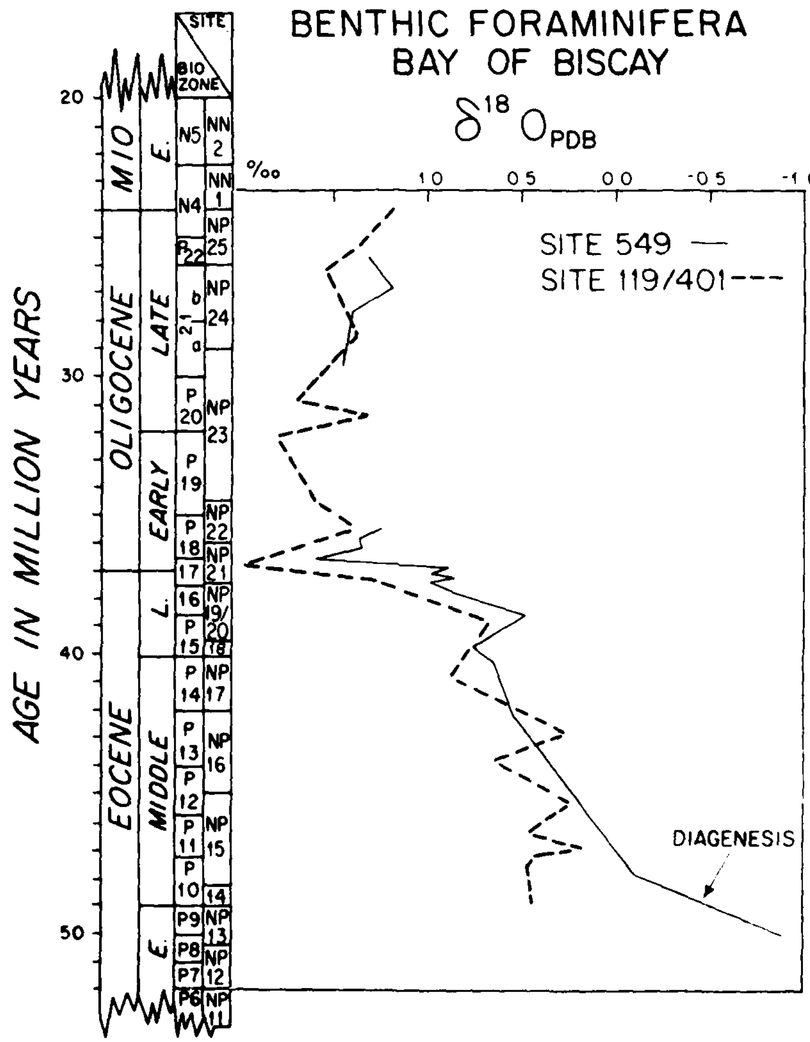


Figure 17. Comparison of Site 549 benthic foraminiferal oxygen isotopic composition with composite record from Bay of Biscay Sites 119 and 401. After Miller et al. (in press).

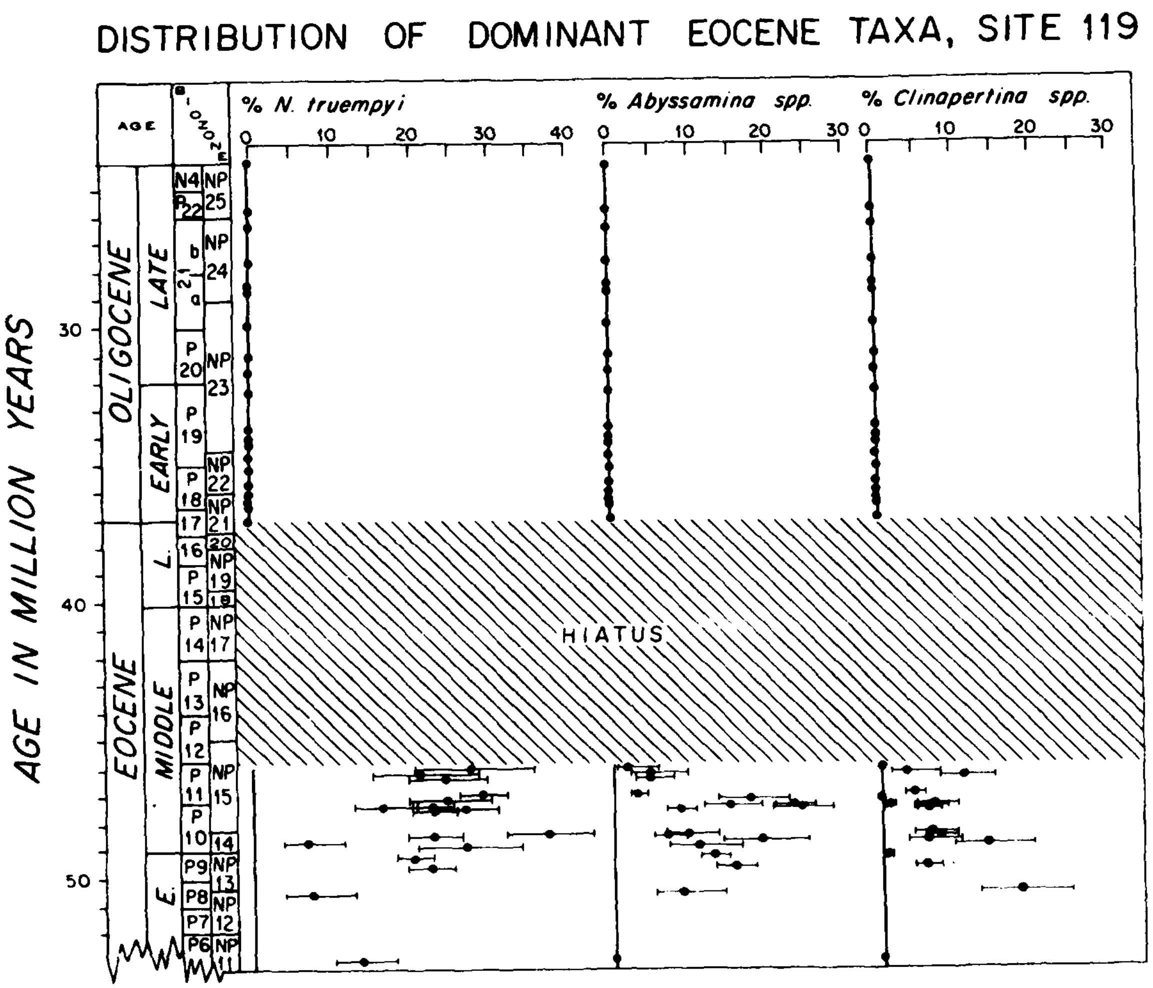


Figure 18. Distribution of dominant Eocene abyssal taxa, Site 119. 80°/o confidence interval is indicated. After Miller (in press).

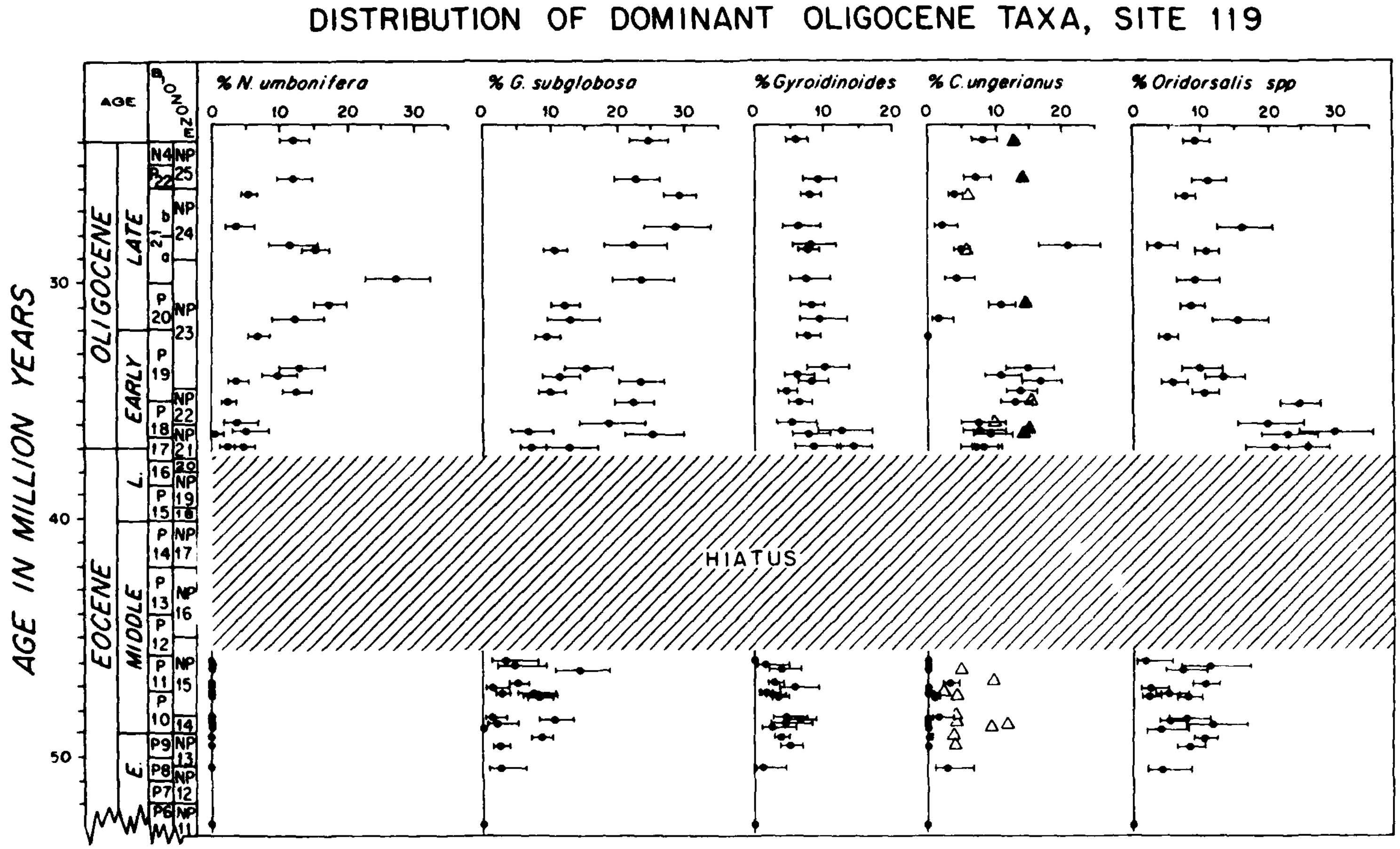


Figure 19. Distribution of dominant Oligocene taxa, Site 119. 80% confidence interval is indicated. After Miller (in press).

SITE 549

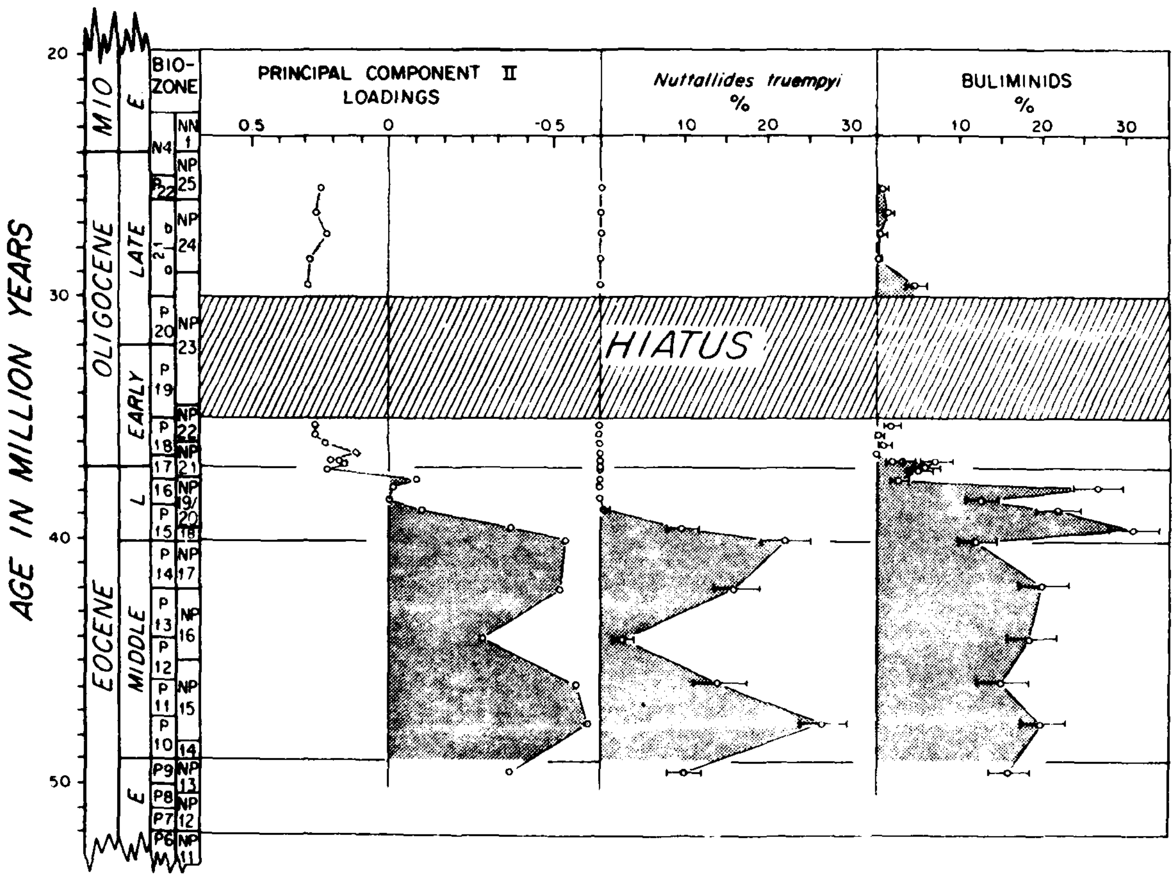


Figure 20. Benthic foraminiferal assemblage composition, Site 549. Principal component analysis was performed on 25 samples from this site. Error bars on percentages indicate 80^{0}/o confidence interval. After Miller et al. (in press).

CHAPTER 4: DISCUSSION AND PALEOCEANOGRAPHIC SYNTHESIS

The major abyssal circulation events deduced from the seismic stratigraphic record and various benthic foraminiferal assemblage and isotopic events span approximately 4 million years (Fig. 21). Nevertheless, there is some evidence that the gradual changes occurring over this interval were punctuated by geologically rapid events as suggested by Kennett and Shackleton (1976). Although the overall ^{18}O enrichment occurred gradually over ~ 2 million year interval (assuming constant sedimentation rates, fig. 2 in Appendix 5), the early Oligocene ^{18}O enrichment occurred at Site 549 in an interval of < 0.5 million years. This agrees well with previous estimates (Kennett and Shackleton, 1976; Keigwin, 1980) for the duration of the $\delta^{18}O$ change in the Southern and Pacific Oceans. In addition, the erosional event associated with reflector R4 probably was also a geologically rapid event, with the change from a sluggishly circulating Eocene ocean to a vigorously circulating Oligocene ocean occurring in less than 2 million years.

In Chapter 2, it was suggested that the northeastern North Atlantic had a major northern source of cold bottom water, and that bottom waters may have entered the North Atlantic by flowing over the Greenland-Scotland Ridge. Presently the Greenland-Scotland Ridge separates the Norwegian-Greenland Sea from the North Atlantic (Fig. 22), and bottom water entering the North Atlantic flows over four sills in this aseismic ridge. These are the Denmark Strait (between Greenland and Iceland), Iceland-Faeroe Ridge, Faeroe Bank Channel, and Wyville-Thompson Ridge (Figs. 22,23) (Crease, 1965; Worthington, 1969, 1970, 1976; Ellett and Roberts, 1973). It has been suggested from thermal subsidence models that the Iceland-Faeroe Ridge did not subside below sea level until the early Miocene (Talwani, Udintsev et al., 1976; Eldholm and Thiede, 1980). This estimate was supported by initial paleontological evidence that indicated that the first surface-water connection of the Norwegian-Greenland Sea with the North Atlantic did not occur until the early Miocene (Bjorklund, 1976; Schrader et al., 1976; Van Hinte In: Talwani, Udintsev et al., 1976). However, reconsideration of the nannofossil, planktonic foraminiferal, and terrestrial floral and faunal

evidence suggest that the first marine connection of the North Atlantic and Norwegian-Greenland Sea across the Greenland-Scotland Ridge occurred in the early Eocene, soon after the opening of the Norwegian-Greenland Sea (Berggren and Schnitker, in press; McKenna, in press; Miller and Tucholke, in press; Appendix 3). This older age estimate for the connection does not conflict with subsidence models, because the Iceland-Faeroe Ridge is the shallowest of the modern sills, and connections may have existed at the westernmost (the Denmark Straits) or easternmost (Faeroe-Shetland Channel) end prior to connections across the Iceland-Faeroe Ridge (Fig. 22)(Miller and Tucholke, in press; Appendix 3).

The most likely candidate for an Early Tertiary seaway linking the North Atlantic with the Norwegian-Greenland Sea is the Faeroe-Shetland Channel (Fig. 23; Ridd, 1981, in press; Miller and Tucholke, in press; Appendix 3; Berggren and Schnikter, in press). The Faeroe-Shetland Channel is a northwest-southeast trending marine channel forming a gateway between the Norwegian-Greenland Sea and the North Atlantic (Fig. 23). It is separated from the North Atlantic by two sills: the Faeroe-Bank Channel (sill depth ~ 830m) and the Wyville-Thompson Ridge (sill depth ~ 350m). Ridd (1981) discussed the origin and history of the Faeroe-Shetland Channel, noting that the channel contains thick (up to 2.5km) post-Paleocene (mostly Eocene) sediments lying upon uppermost Paleocene (= Thulean) basalts. Some debate exists as to the nature of the underlying crust, for Talwani and Eldholm (1972) and Ridd (1981) suggested that the channel is floored by continental crust, while Roberts (1975), Bott (1975), and Russell and Smythe (1978) favored an oceanic origin. As a result, the pre-Paleocene subsidence history of this region is unconstrained. Still, similarities in the seismic and rock stratigraphic records in the North Atlantic and the Faeroe-Shetland Channel suggest that these regions were connected by the end of the Eocene. Ridd (1982) observed a major change in sedimentary regime in the Faeroe-Shetland Channel associated with a prominent seismic horizon. The sequence overlying this reflector is thinned into lenticular bodies thought to reflect the influence of strong currents (Ridd, 1981). The reflector can be traced to the north flank of the Wyville-Thompson Ridge (Fig. 24), while reflector R4 can be traced to the south flank of the

ridge (Ellett and Roberts, 1973). It seems likely that the two horizons are related in time and genesis. However, the age control on the horizon in the Faeroe-Shetland Channel is poor. Although, Ridd (1981) suggested that the change in sedimentary regime correlates in time with reflector R4, Ridd (in press) favored a later timing (near the end of the Paleogene) for this event.

Berggren and Hollister (1974) and Miller and Tucholke (in press; Appendix 3) suggested that the major change in abyssal circulation in the North Atlantic was related to an Arctic connection. Berggren and Hollister (1974) used an early Eocene age for the separation of Greenland and Spitsbergen, the Arctic connection, and the abyssal circulation change. However, Talwani and Eldholm (1977) later concluded that Greenland separated from Spitsbergen prior to Anomaly 13 time (in the late Eocene to early Oligocene). Miller and Tucholke (in press; Appendix 3) noted the time correlation between reflector R4 and the opening of this Arctic passage, and they suggested that following the separation of Greenland and Spitsbergen, Arctic waters rapidly entered the Norwegian-Greenland Sea, flowed through the Faeroe-Shetland Channel, across the Wyville-Thompson Ridge and entered the North Atlantic. The history of connection of the North Atlantic and the Arctic Ocean is a controversial issue (cf. Gartner and Keany, 1978; Gartner and McGuirk, 1979; Thierstein and Berger, 1978; with Ling, et al., 1973; Clark and Kitchell, 1979; Gradstein and Srivastava, 1981). However, shallow-water connections probably existed as early as the Mesozoic through the Labrador Sea (Gradstein and Srivastava, 1981) and possibly through epicontinental seas such as the Barents Sea (F.M. Gradstein, personal communication). Still, tectonic control (viz. opening of a deep passage to the Arctic Ocean) on introduction of bottom water to the North Atlantic would explain both the geologic suddenness and intensity of the abyssal circulation event that created reflector R4 (Miller and Tucholke, in press; Appendix 3).

The late Eocene to early Oligocene ^{18}O enrichment has been observed in several different ocean basins over a wide range of paleodepths, and probably cannot be attributed only to initial entry of Arctic/Norwegian-Greenland Sea sources of cold bottom water. There is evidence that initial formation of cold, vigorously circulating bottom water from both

northern sources (as denoted by reflector R4 and Horizon A^u) and southern sources (as denoted by erosion of widespread unconformities and other changes in the Southern and Pacific Oceans; Kennett and Shackleton, 1976; Moore et al., 1978) began near the end of the Eocene. These events were reflected by a major ^{18}O enrichment. The synchronous ^{18}O enrichment associated with cold bottom water formation in both the Antarctic and the polar/subpolar marginal basins of the North Atlantic may argue against a tectonic cause of the abyssal circulation change. Still, high-salinity water provided by modern North Atlantic Deep Water is important in the formation of Antarctic Bottom Water (Foster and Carmack, 1976); such linkages or "teleconnections" (see Johnson, 1982; Schnikter, 1980a,b) might be invoked to explain the formation of southern bottom-water sources following the tectonically-controlled entry of northern sources of bottom water into the North Atlantic.

The development of cold, vigorous bottom water circulation near the end of the Eocene falls within a period of global climatic cooling. Several lines of evidence, including $\delta^{18}O$ of planktonic and benthic foraminifera, distribution of calcareous nannoplankton, distribution of planktonic foraminifera, and paleobotanical evidence obtained from terrestrial floras indicate that general global cooling and increased latitudinal thermal gradients developed between the middle Eocene and the early Oligocene (see Table 1 in Appendix 3 for full references). However, the details of the climatic record are in dispute. Collison et al. (1981) suggested from palynological studies in southern England that climatic cooling was gradual, beginning in the early Eocene and extending into the early Oligocene. Norris (1982) used palynomorphs from the Mackenzie Delta and Wolfe (1978) used terrestrial floras from the northwestern United States to suggest that a major, sharp cooling occurred at the end of the Eocene. Some of this disagreement may be attributable to the nature of the record studied and differences in interpretation. Still, comparison of various studies (Collison et al., 1981; Norris, 1982; Wolfe, 1978; Haq et al., 1977; Haq, 1981) shows general agreement that: 1) following a climatic optimum of the early Eocene (and possibly earliest middle Eocene), general cooling occurred into the Oligocene; 2) offsets to cooler conditions occurred near the

middle/late Eocene boundary, near the Eocene/Oligocene boundary, and in the middle Oligocene; 3) the late Oligocene was a period of warming.

The role of climatic change in the development of abyssal circulation is not clear. The faunal changes discussed here occurred in a 4 million year period and may be related, not to a sudden climatic or bottom water temperature change, but to a general climatic and bottom water cooling between the middle Eocene and early Oligocene (see also Corliss, 1979b; 1981). The geologically rapid abyssal circulation event associated with reflector R4 may be explained by tectonic threshold control, and would appear to be causally distinct from the faunal and isotopic changes resulting from gradual climatic cooling. Still, it may be possible to relate the abyssal circulation event to a rapid climatic cooling at the end of the Eocene. Brass et al. (1982) argued that climatic cooling, resulting in increased thermal gradients and the formation of cold bottom water at high latititudes, can result in geologically rapid and catastrophic abyssal circulation changes. The sharp cooling noted near the end of the Eocene may have resulted in the rapid replacement of warm, saline bottom water (WSBW) produced in marginal subtropical seas by cold bottom waters produced in polar/subpolar basins (see Brass et al., 1982 for discussion of WSBW).

This study documents that a major early Oligocene hiautus occurs along the margin of the Rockall Plateau (Fig. 2) and in the Bay of Biscay/Goban Spur region (Fig. 3). Considering the widespread distribution of reflector R4 and its general correlation with an unconformity, it seems likely that the early Oligocene is missing from much of the northern North Atlantic. Similarly, in the western North Atlantic, the Oligocene series is virtually absent along the continental rise and deep basin (Tucholke, 1979). Where are Oligocene sediments? The problem is compounded by the scarcity of Oligocene sediments on continental shelves in the North Atlantic (Olsson et al., 1980; Gradstein and Srivastava, 1981). Tucholke and Vogt (1979) suggested that the sediments might have been carried into the South Atlantic. However, recent seismic studies (Gamboa, in press) show that a major unconformity and associated seismic reflector occurs in the Brazil Basin (northwest South Atlantic); this unconformity separates upper Oligocene from lower

Eocene strata. It seems unlikely therefore that the sediments were deposited there. The more southerly Argentine Basin is poorly known, and it is possible that this was the locus of deposition. It is also possible that some of the sediment was deposited on the northern Bermuda Rise (Tucholke and Vogt, 1979). The absence of Oligocene sediments may, in part, be a sampling artifact. Most DSDP holes have been drilled along the margins of the sediment drifts (e.g. Sites 117, 403-405) or where the sediment section is thinned. It has been demostrated that this is where the unconformity is best developed. In sites more toward basin centers, the unconformity becomes an apparent conformity (e.g. Sites 112 and 116). Thus, sediments may have been deposited in drifts in the center of the basins (e.g. the R3-R4 interval in Figures 6,8,9, Table 1) outside the erosional zone. If spread uniformly throughout the western North Atlantic (reconstruction of Sclater et al., 1977), the sediment eroded from the northern North Atlantic (~ 120,000km^3) and the western North Atlantic (~ 200,000km^3; Tucholke and Mountain, 1979) would have formed a layer ~ 60m thick.

The abyssal circulation model presented here requires that the polar-subpolar basins of the North Atlantic and adjacent seas "export" bottom water to other ocean basins beginning in the latest Eocene to earliest Oligocene. Using the model of Berger (1970) it would be expected that such "export" regions should have low siliceous productivity (such as the modern North Atlantic), while high siliceous productivity would be associated with general upwelling regions (such as the modern North Pacific). Yet, widespread deposition of biosiliceous sediments occurred in the early to early middle Eocene of the western and northern North Atlantic, while the patchy deposition of biosiliceous detritus occurs throughout the middle Eocene to early Miocene of most of the northern North Atlantic. The only significant exception occurs in the Labrador Sea (Site 112) where abundant biogenic silica is confined to the Oligocene to Miocene section. Significant biosiliceous productivity terminates at about the level of reflector R2 (upper lower Miocene). This led Schnitker (1980a,b) to suggest that the North Atlantic became an "exporter" of bottom water beginning in the early to early middle Miocene. Thus, the presence of signficant biosiliceous material would

argue for upwelling, not export, of bottom waters in the northern North Atlantic during the early Eocene to early Miocene. This apparent contradiction of the abyssal circulation model may be resolved, for the Berger (1970) model is probably an over-simplification when applied to the Late Paleogene North Atlantic. 1) Basin to basin fractionation may have been significantly different in the Late Paleogene, for strong westward-flowing circumeqatorial currents connected the North Atlantic and Pacific Oceans (Berggren and Hollister, 1974; 1977). In fact, the siliceous belt may be related to upwelling resulting from the circumequatorial current (Cita, 1971; Berggren and Hollister, 1974; Tucholke and Vogt, 1979). Restriction of circumequatorial flow by sealing off of the eastern Tethys in the early Miocene (Berggren and Hollister, 1974; Berggren and Van Couvering, 1974) may have resulted in termination of the circumequatorial current, upwelling, and siliceous deposition. 2) Due to upwelling, the Antarctic region is presently a region of very high siliceous productivity (Lisitzin, 1972); yet, formation of Antarctic Bottom Water in the marginal Weddell Sea (Foster and Carmack, 1976) causes the Antarctic region to be an "exporter" of cold, vigorously circulating bottom water. In a similar fashion, upwelling and high productivity may have occurred in the Eocene through Oligocene North Atlantic, but downwelling and bottom-water formation may have occurred in the Oligocene in marginal basins viz. the Norwegian-Greenland Sea or Arctic Ocean. 3) Alternatively, the increase in siliceous deposition may be related to increased volcanism (Gibson and Towe, 1971).

The most dramatic depositional phase of sediment drift and wave development began in the northern and western North Atlantic near the early/middle Miocene boundary (above reflector R2)(Fig. 7; Table 1; fig. 12C in Appendix 3); this depositional phase is interpreted as resulting from a general decrease and stabilization of the abyssal circulation. The major depositional phase correlates with a trend toward east-west basin isolation due to the restriction of fracture zone conduits across the Reykjanes Ridge (Miller and Tucholke, in press; Appendix 3). Still, it is not clear how the closing of fracture zone conduits may have attenuated the abyssal circulation, nor is it clear that this was the

sole factor responsible for reduced deep circulation. Shackleton and Kennett (1975), Savin et al. (1975), and Woodruff et al. (1981) noted a dramatic shift in oxygen isotopic composition of benthic foraminifera that began in the middle Miocene. Although they attributed this shift primarily to buildup of the Antarctic ice cap, Woodruff and Douglas (1981) suggested that at least some of the shift represents a major bottom-water cooling and a "thickening of Antarctic Bottom Waters. Such an implied increase of Antarctic sources of bottom water may have resulted in reduced influence of bottom water derived from northern sources.

Many faunal and isotopic problems remain unresolved or remain to be tested by future work. The timing and significance of the major changes in benthic foraminifera (replacement of the *Nuttallides truempyi* assemblage, acme of *Nuttallides umbonifera*) need to be corroborated in other locations. The most critical unresolved faunal problem is the timing of the replacement of the *Nuttallides truempyi* assemblage and the extinction of the Eocene abyssal taxa. Although these events are most dramatic in the deepest sites, no site with continuous recovery of the upper Eocene section from paleodepths greater than 3 kilometers has been studied. Such a site needs to be identified and studied in order to resolve the timing of these events.

Two fundamental problems in using benthic foraminifera to interpret paleoceanographic changes are illustrated by the faunal studies contained here (Appendixes 1,4,5). 1) Size-fraction biases may significantly alter results. Comparison of data from Site 548 from Appendix 5 (> 150 μm size fraction) with data of Poag (in preparation) from the greater than 63 μm size fraction shows significant differences. Unfortunately, the choice of size fraction remains arbitrary and there is little uniformity among investigators. 2) The major changes in Cenozoic deep-sea benthic foraminifera often do not coincide with other evidence of paleoceanographic changes. This is illustrated by four cases. a) Tjalsma and Lohmann (1982) noted a major benthic foraminiferal extinction event near the end of the Paleocene; no change in $\delta^{18}O$ or other known paleoceanographic event is associated with this change. b) The major benthic foraminiferal changes discussed here began prior to the major

$\delta^{18}O$ increase and the change in intensity of abyssal circulation. c) Important changes in benthic foraminiferal assemblages in the middle Miocene apparently post-date a major enrichment of ^{18}O, inferred to be a major temperature drop (Douglas and Woodruff, 1981). d) There is little correlation between glacial and interglacial cycles and benthic foraminiferal response in the Pleistocene Atlantic Ocean (Lohmann, 1978; Peterson and Lohmann, 1981; Bremer, 1982). These cases illustrate that benthic foraminiferal changes alone cannot be used to interpret abyssal circulation changes unequivocally. Future studies need to use other corroborative data including isotopic studies, planktonic stratigraphy, seismic stratigraphy, lithostratigraphy, geophysically-constrained subsidence models ("backtracking") and well histories ("backstripping") to help gain an understanding of the benthic foraminiferal response to oceanographic changes.

The abyssal circulation model presented here is not completely developed or correct in detail, and continued testing of the model is needed. Several important questions associated with the model remain unanswered or need further documentation. A better understanding of the abyssal circulation history obviously can be developed by the acquisition of additional, carefully placed geological (borehole) and geophysical data. In particular, three kinds of analyses would significantly improve the perception of the abyssal circulation history. 1) Basin-wide mapping and sequence analyses using the seismic stratigraphic record in the North Atlantic, Faeroe-Shetland Channel, and Norwegian-Greenland Sea would provide clearer definition of the intra-basin geometries of current effects, and would allow an inter-basinal comparison that should result in a better understanding of tectonic threshold events. Eventually this approach could be extended to the Brazil and Argentine Basins of the South Atlantic in order to establish the relative importance and timing of northern and southern sources for vigorously circulating bottom water. 2) Improved subsidence models of the Greenland-Scotland Ridge would allow better definition of the timing of shallow and deep marine connections across the ridge. 3) Studies, such as those conducted here for the Late Paleogene, of existing Miocene DSDP material from the North Atlantic would allow the testing of the abyssal circulation model using

isotopic and lithostratigraphic data, and a determination of the relationship of Miocene benthic foraminiferal changes with the abyssal circulation model and isotopic changes. 4) Continued benthic faunal, planktonic floral and faunal, and isotopic studies of critically placed DSDP holes proposed for the last phase of GLOMAR Challenger drilling and for GLOMAR Explorer drilling in the southern Labrador Sea, the Greenland-Scotland Ridge, and the northeastern North Atlantic would help clarify the Tertiary patterns of paleocirculation, the potential northern-hemisphere climatic effects on bottom-water formation, and the history of surface and deep water connections of the Norwegian-Greenland Sea with the North Atlantic.

Future work will address the age of the circulation event in the Faeroe-Shetland Channel and its relationship to the change in abyssal circulation associated with reflector R4 in the North Atlantic. This should conclusively show if the events are related in time and genesis, and if the Faeroe-Shetland Channel was a conduit for northern bottom waters flowing into the North Atlantic at the time that reflector R4 was formed.

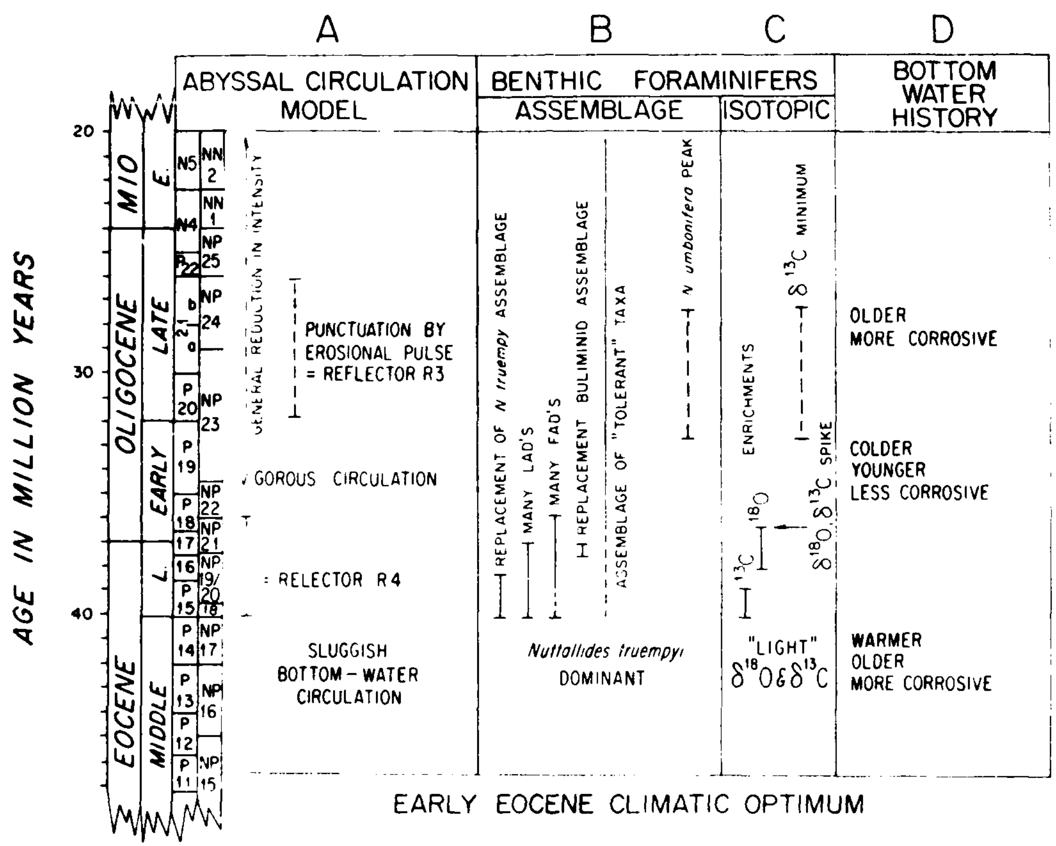


Figure 21. Summary of paleoceanographic events. Column A indicates abyssal circulation events inferred from Chapter 2, column B indicates benthic foraminiferal changes, column C indicates timing of major benthic foraminiferal isotopic events, and column D indicates bottom water history inferred from the data in columns B and C. After Miller et al. (in press).

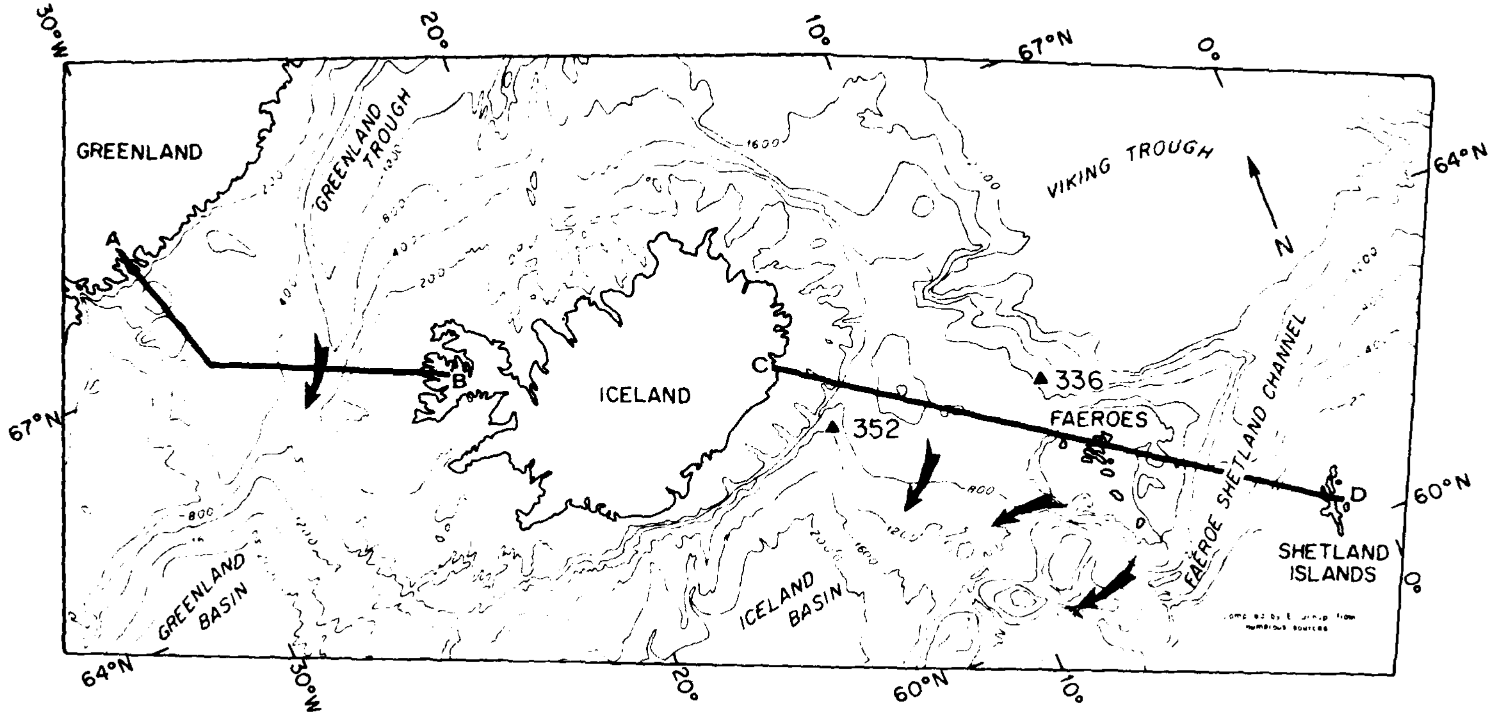
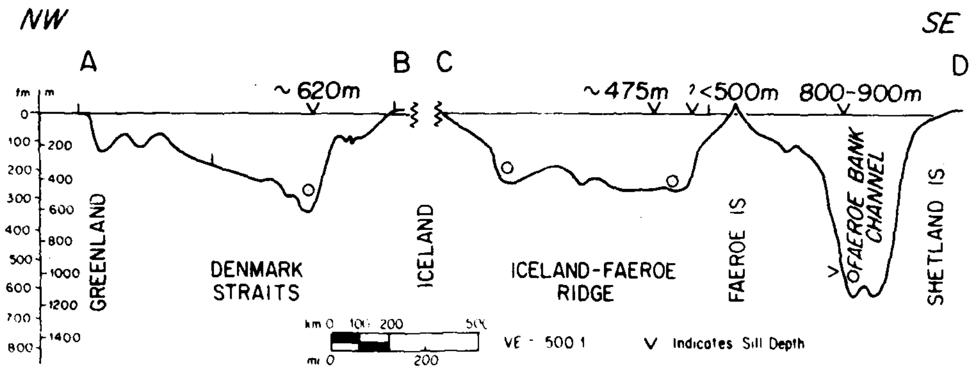


Figure 22a. Bathymetry of Greenland-Scotland Ridge, in meters (from Uchupi and Hays, unpublished data). Sections A-B and C-D are illustrated in Figure 22b. DSDP sites 352 and 336 are indicated with triangles. Arrows indicate modern overflow routes (see text).



CROSS SECTION: GREENLAND-SCOTLAND RIDGE

Figure 22b. Bathymetric cross-section of the Greenland-Scotland Ridge (located in Figure 22a) showing maximum present sill depths.

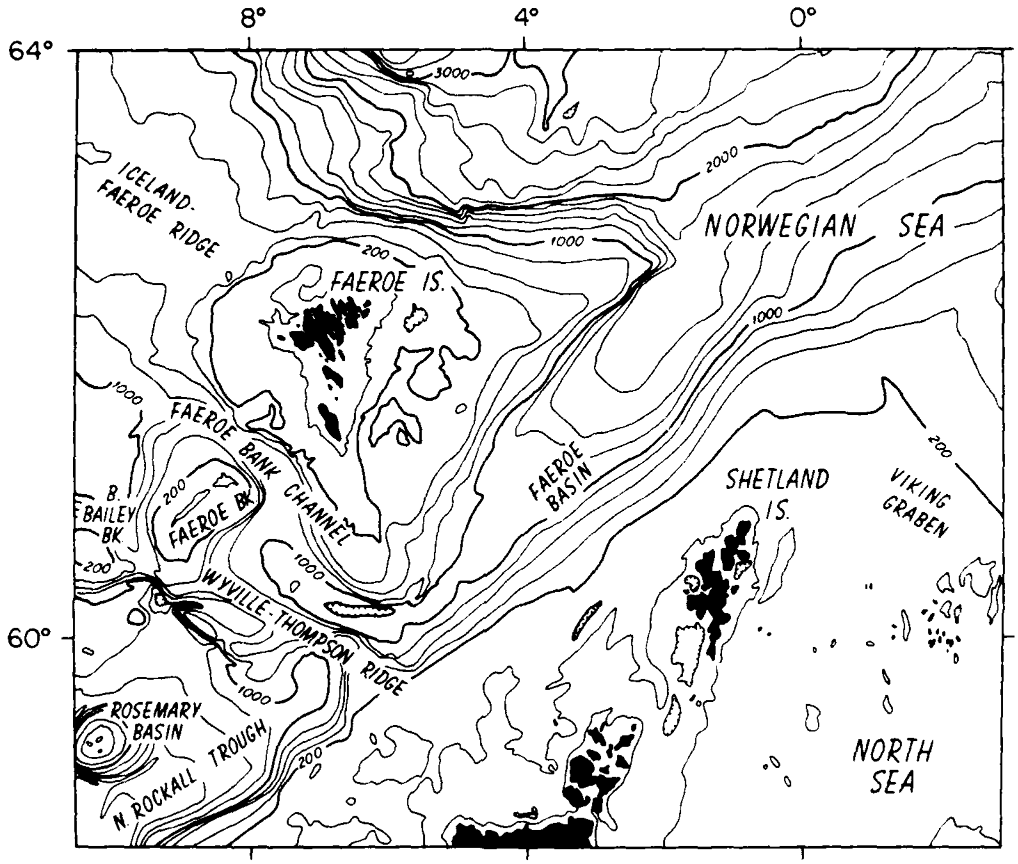


Figure 23. Bathymetric map of Faeroe-Shetland Channel and environs. After NAVOCEANO Map NA5 (1977).

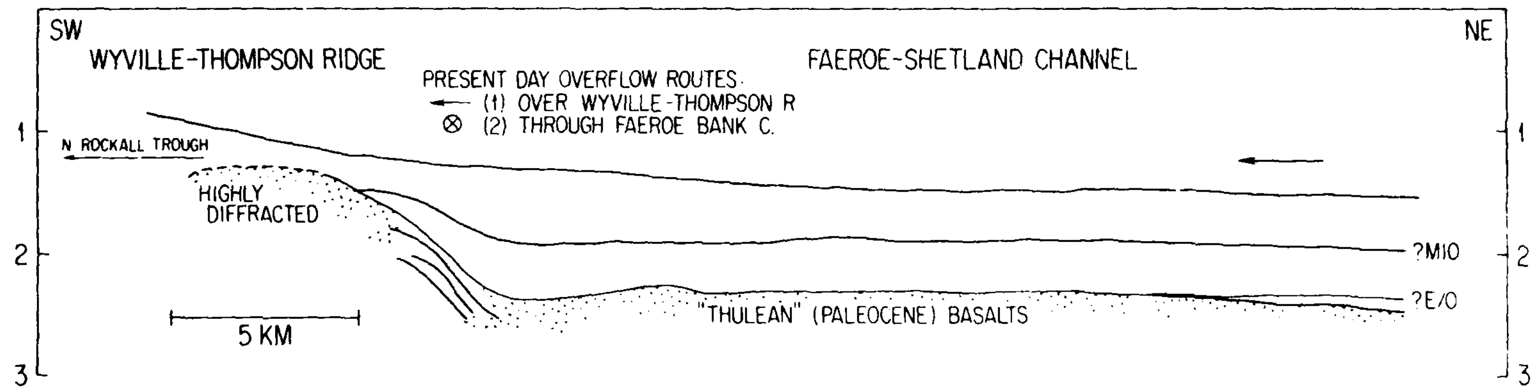


Figure 24. Interpretation of multichannel profile in the southern Faeroe-Shetland Channel. Data provided by D. Smythe and M. Ridd.

CONCLUSIONS

1. Based upon seismic stratigraphic studies of the northern North Atlantic, a model for the development of abyssal circulation in the North Atlantic is developed.

   a. The widely distributed reflector R4 correlates with an unconformity that can be traced to its correlative conformity at the top of the Eocene. Reflector R4 reflects a major change in abyssal circulation, from sluggishly circulating bottom water in the Eocene to more vigorously circulating bottom water in the Oligocene. Sediment distribution studies indicate a northern source for this bottom water, probably from the Arctic Ocean via the Norwegian-Greenland Sea and Faeroe-Shetland Channel.

   b. Increased rates of deposition associated with the development of large sedimentary drifts in the later Oligocene (above reflector R3) through Miocene (especially above reflector R2 = late early Miocene) are interpreted as reflecting a general reduction in intensity of abyssal circulation. This general reduction may have been punctuated by brief erosional pulses.

2. A major $\delta^{18}O$ increase begins at ~ 38 Ma (late Eocene), culminating in a rapid (< 0.5 my) increase in $\delta^{18}O$ just above the Eocene/Oligocene boundary (~ 36.5 Ma) in the Bay of Biscay/Goban Spur regions (DSDP Sites 119/401 and 549). A rapid $\delta^{13}C$ increase also occurs just above the boundary in these sites. These changes represent the transition from warm, old (low O_2, high CO_2, low pH, hence more corrosive) Eocene bottom waters to colder and younger (higher O_2, lower CO_2, higher pH, hence less corrosive) bottom waters in the early Oligocene.

3. Benthic foraminiferal changes occurring in the Late Paleogene in the northern North Atlantic include:

   a. In the southern Labrador Sea (DSDP Site 112), an assemblage of predominantly agglutinated benthic foraminifera is replaced by a deep-sea calcareous assemblage between the middle Eocene and the early Oligocene.

b. In abyssal sites greater than 3km, an indigenous Eocene calcareous fauna including <u>Nuttallides truempyi</u>, <u>Clinapertina</u> spp., <u>Abyssammina</u> spp., <u>Aragonia</u> spp., and <u>Alabamina dissonata</u> becomes extinct between the middle Eocene and early Oligocene.

c. In shallower sites (< 3km paleodepth) in the Goban Spur/Bay of Biscay regions and elsewhere in the Atlantic, a <u>Nuttallides truempyi</u>-dominated assemblage is replaced in the early late Eocene (~ 38.5-40 Ma).

d. In the late Eocene to early Oligocene, a <u>Globocassidulina subglobosa</u>-<u>Gyroidinoides</u>-<u>Cibicidoides ungerianus</u>-<u>Oridorsalis umbonatus</u> assemblage dominates the northern North Atlantic. These taxa are bathymetrically wide-ranging and stratigraphically long-ranging, and may be interpreted as tolerant of environmental changes.

In general, these changes are thought to reflect the transition from an Eocene ocean more corrosive to calcium carbonate to a less corrosive Oligocene ocean.

e. A middle Oligocene acme in <u>Nuttallides umbonifera</u> in the deepest sites (> 3km paleodepth) and a concomittant minimum in $\delta^{13}C$ are interpreted as reflecting older, more corrosive bottom water.

4. The faunal and isotopic data are combined with the abyssal circulation model in the following scenario:

a. Old, warm, corrosive, and sluggishly circulating bottom water was replaced by younger, colder, and more vigorously circulating bottom water which had a northern source (Arctic and/or Norwegian-Greenland Sea). This developed throughout the late Eocene (40-37 Ma), but was punctuated by a rapid event (= reflector R4 and the concomittant $\delta^{18}O$ increase) just above the Eocene/Oligocene boundary (~ 36.5 Ma).

b. During the middle Oligocene, bottom water circulation was reduced, and the age and corrosiveness of bottom water increased.

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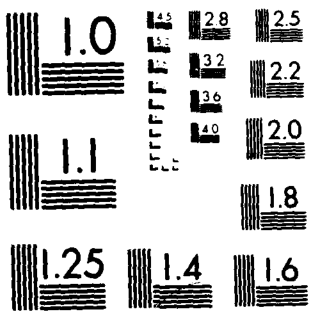

MICROCOPY RESOLUTION TEST CHART
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APPENDIXES 1 TO 5

ARE AVAILABLE FROM THE FOLLOWING SOURCES:

Appendix 1: Micropaleontology, 28: 1-30

Appendix 2: Nature, 296: 347-352

Appendix 3: In: Saxsov, S., ed., "The Structure and Development of the Greenland-Scotland Ridge: New Methods and Concepts", NATO Conference Series: Marine Science, Plenum Press (in press).

Appendix 4: Marine Micropaleontology (in press).

Appendix 5: In: de Graciansky, P.C., Poag, C.W., et al., Init. Repts. DSDP (in press).

Reprints of Appendixes 1 and 2 are available from the author.

Preprints of Appendixes 3 to 5 are available from the author and from the Ocean Industry Program, Woods Hole Oceanographic Institution.

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LATE PALEOGENE (EOCENE TO OLIGOCENE) PALEOCEANOGRAPHY OF THE NORTHERN NORTH ATLANTIC by Kenneth George Miller. November 1982. 299 pages. Prepared for the Office of Naval under Contract N00014-79-C-0071 and was partially funded by a Phillips Petroleum Fellowship.

Seismic stratigraphic evidence indicates that a major change in abyssal circulation occurred in the latest Eocene-earliest Oligocene of the North Atlantic. Reflector R4 reflects a change from weakly (Eocene) to vigorously circulating bottom water (early Oligocene). Sediment distribution studies indicate a northern source for this bottom water, probably from the Arctic via the Norwegian-Greenland Sea/Faeroe-Shetland Channel. Current-controlled sedimentation and erosion continued through the Oligocene; however, above reflector R3 (upper Oligocene), the general intensity of abyssal currents decreased. Above reflector R2 (lower Miocene) a further reduction in abyssal currents resulted in more coherent current-controlled sedimentation and a major phase of sediment drift development. Paleontological and stable isotopic data support these interpretations. In the Bay of Biscay, a major $\delta^{18}O$ increase began in the late Eocene, culminated in a rapid increase just above the Eocene/Oligocene boundary. Major deep-sea benthic foraminiferal changes occurred between the middle Eocene and earliest Oligocene: an agglutinated assemblage was replaced by a calcareous assemblage (abyssal Labrador Sea), and an indigenous Eocene calcareous fauna became extinct (abyssal Bay of Biscay). In shallower Atlantic sites (< 3km paleodepth), a Nuttallides truempyi assemblage was replaced by an assemblage of long- and wide-ranging taxa in the early late Eocene. These faunal and isotopic changes represent the transition from warm, old, corrosive Eocene bottom waters to colder, younger (lower CO_2, higher pH, hence less corrosive) early Oligocene bottom waters.

1. Paleoceanography
2. Benthic foraminifera
3. Seismic stratigraphy
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